Transformation from High Density Polyethylene Waste to a Multifunctional Diamond

A Journey of Bringing Plastic Recycling Back to the State of Hawaiʻi

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School of Architecture
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Doctorate Project Committee:

Spencer Leineweber, Chairperson
William Chapman
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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in partial fulfillment for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Mānoa.

Doctorate Project Committee

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Acknowledgement

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During my research, I have conducted telephone interviews with several professionals who provided very helpful information on both recycling and the HDPE material. I greatly appreciate the generous and patient help of government representatives, such as Suzanne Jones, the Recycling Coordinator of the City and County of Honolulu; Adam Bien, the Recycling Specialist of the City and County of

Honolulu; Bruce Iverson, the Director of Marketing and Development of Reynolds Recycling; and Jaqueline Simone Ambrose, the Project Manager of the Maui Recycling Group's Aloha Shares Network. They explained the reasons why plastic recycling has not been successful in the State of Hawaiʻi, which helps me to adjust my design intents according to the restrictions. It is also helpful to know that the state government is taking a series of measures to decrease the plastic waste going into the landfills, since it gives additional logical meanings to this thesis.

My personal knowledge of recycled HDPE material is largely the result of my work with Todd Reed, son of the former President of Aloha Plastic Recycling on Maui, and Patrick Egge, Office Manager of Kane International Corp. Their information on the recycling process of HDPE waste and recycled HDPE lumber and the sample of the recycled product helps me to obtain a realistic understanding of local plastic recycling industry, as well as the pros and cons of the existing products.

Last but not least, I would love to express my appreciation for my family, classmates, and friends. They have been very supportive and caring over the past seven years, and my success would be meaningless without them.

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Abstract

Plastic is a legendary material with contradictory impacts to the modern world. It consists of great characteristics for an extremely wide range of applications, but it also causes environmental issues. Plastic up-cycling has become a popular solution to these issues. The growing trend of creatively integrating recycled plastic objects with conventional living environment has spread globally.

Among a variety of plastic types, the high density polyethylene (HDPE) is mainly discussed in this thesis as an example to show the factors that need to be considered during the design of a recycled plastic product. The adventure goes through a series of studies on environmental condition, existing case studies, material characteristics, and regional recycling capabilities, mainly in the State of Hawaiʻi.

The thesis involves a constant exchange between problem finding and solving. With the proposed solution, there comes another challenge. Step by step, the thesis goes through a journey that discovers problem, resolves problem, meets challenge, and achieve a possible solution. Therefore, the balance between the pros and cons is the main task in the research and design portions, which presents a process of decision making in the plastic up-cycling.

Introduction

Project Goals

The overall goal of the project is developing an appropriate design that utilizes recycled HDPE sustainably, innovatively and viably, based on a relatively realistic perspective of the current condition. The selection of material and decision of design in this project is based on a series of research that analyzes the necessity of each main feature. The thesis starts from a simple idea, conducts a background exploration, studies the examples of problem solution, and suggests a design that meets certain requirements. The project in this thesis proposes a design that is not limited to existing usages but respectful to the current situation; the design also follows the trend of multi-functional product, which has a higher flexibility and value than conventional recycled products.

The research portion aims to have an overall understanding of the recycling background and the relevant designs that utilize recycled wastes. The thesis introduces the recycled HDPE made from post-consumer household milk bottles, especially in the State of Hawaiʻi. The existing condition of why recycling, what to recycle, and how to recycle will be the fundamental guidelines for the design phase, which will proposed solutions to the current issues.

The goal of the design portion is to find a balance between the existing restrictions and the proposed functions. A careful design is the key to revitalize the plastic materials. There have been many designers who tried to integrate their designs with unconventional materials that respond to the environmental issues. Regardless the adventurous hypotheses and careful testing that the designer, engineer and manufacturer have to undergo, the design addressing the solutions to the material, technical, or application issues is crucial for the recycled product.

Research Methods

After talking about the inefficient recycling rate of the U.S. and Hawai'i State, the thesis adopts quantitative research to clarify why HDPE containers in Hawai'i are in great need of recycling. Various data is provided to show the serious environmental problems created by plastics. Phone interviews with Hawaiian recycling agencies are conducted to inquire information on plastic waste and recycling, as well as the serious challenges with recycling of milk and detergent containers.

In order to introduce the three types of recycling processes of plastics, the case studies in this thesis look into several constructions that utilize alternative materials. The three processes include minimal, mechanical and chemical approaches. In this study, it mainly explores how architects alter the materials or building method to overcome the limitations of the materials, in order to achieve remarkable design results through innovative solutions. Moreover, an Alternative Experience program was conducted in spring 2011 semester at MINIWIZ Sustainable Energy Development Ltd., a company that invented recycled plastic bottle brick, in order to understand plastic recycling from a professional perspective. This chapter aims to provide architectural examples that apply alternative materials. These materials achieve the basic safety regulations of a building, which does not sacrifice the goals of using recycled and recyclable building materials.

A comparative research on HDPE will explain the pros and cons of this material. The physical and mechanical properties of the materials will be compared to other conventional materials to show the elements that can be utilized or improved. Plenty of material specs from various manufacturer web pages are used for reference. Interviews with Todd Reed, one of the owners of the former Aloha Plastics Recycling, and Patrick Egge, Office Manager of Kane International Corp, provide an in-depth understanding of HDPE recycling and properties of plastic lumber.

To further analyze the feasibility between minimal reuse and mechanical recycling in the State of Hawai'i, the thesis undergoes a series of experiments that study the form of the bottle by dividing a bottle into pieces, and it also test the material reaction to high temperature by burning the bottles. The experiment helps to obtain a hands-on experience of the material and bottle form, which concludes the design wisdom that uses an extremely thin material to achieve a high capacity, as well as the difficulty of simple reuse because of the irregular form. Hence, the conclusion leads to the demand of mechanical recycling.

Literature Review

The United States Environmental Protection Agency (EPA) has published numerous waste and recycling information on their official website *http://www.epa.gov*. Not only does this website show the waste information, but this organization is also one of the federal agencies that establish environmental regulations for industry and business. There are various reports about different types of waste, like paper, plastic, aluminum and tires. These reports focus on plastics and paper because they are a larger portion than the rest of the MSW stream, but they have a proportionally low recycling ratio. Although the recycling of plastic has been increased in the past decade, the growing pace of the plastic consumption is far beyond society's capability to deal with the waste.

Meanwhile, the *Natural New*, the *Independent*, and other news media reported the "plastic soup" in the Pacific Ocean. [1] The plastic layer accumulated from waste streams floats on top of the ocean, and it will not biodegrade in the coming decades. What's worse, the plastic pieces attract toxics in the water and become more harmful than they originally are. The plastic layer severely impacts the ecosystem in the ocean. The increasing environmental threats call for a higher attention to the plastic waste, which encourages the emergence of the plastic recycling industry. The facts has pointed out

[1] "The world's rubbish dump: a tip that stretches from Hawaii to Japan," The Independent, February 5, 2008, http://www.independent.co.uk/environment/the-worlds-rubbish-dump-a-garbage-tip-that-stretches-from-hawaii-to-japan-778016.html (accessed November 16, 2010).

that landfill is definitely not the right way to handle plastic wastes; therefore, reuse and recycling of plastics are the mandatory tasks for the future.

The book Materials for Sustainable Sites written by Meg Calkins introduces several major types of construction materials, such as wood, steel, masonry, glass, stone, plastic, etc. The book talks about the manufacture process, material properties, usage, energy consumption, environmental influence, and so on. The information provides a reference to further understand plastic. The book also introduces plastic lumber, a popular recycled plastic product that is widely used in outdoor construction. There are introductions of both recycled material and regular materials in the book, and it shows a parallel demand between alternative and conventional materials in the construction industry. The book not only states the advantages and limitations of the material, but it also leads to the possibilities and concerns of the future improvement of these materials.

The books Shigeru Ban Architect: Paper Tube Architecture 10: Works 1990-2000 and Shigeru Ban Paper in Architecture introduce various projects designed by Shigeru Ban. The authors and Ban discuss the project process and evolutionary use of paper tubes in the books. It is interesting to understand the philosophy and projects from various perspectives. From recycled fabric core to manufactured building material, the paper tubes are improved step by step to achieve UV-proof, water-prove, fire-resistant and strength. The constructional system has also been specifically designed to suit the change of material, functions, allowable conditions, and so on.

Chapter 1 Background Studies

Technological development and globalization continue to accelerate the production, exchange, consumption, and disposal of all products. Meanwhile, with convenient access to disposable products, conservation has become a huge challenge to people's everyday living. The resulted waste and pollution have increased the pace of environmental damage.

The plastic patches in the Pacific Ocean have caused global attention to the plastic wastes. The toxic marine environment severely impacts the ecosystem. An effective handling of plastic waste is important to improve the existing and future situations.

One of the reasons why recycling has a relatively low capacity is because the recycling industry faces several technological and social challenges. The thesis focuses on the State of Hawaiʻi, since it represents the isolated regions that have limited local resources and restricted transportation. Studies show the growing demand of local plastic recycling.

A brief introduction to plastic gives a general understanding of the importance of plastic recycling, and the categorization system of plastics for recycling.

1.1 Recycling of Municipal Solid Waste

Unlike Construction and Demolition (C&D) Wastes, which are regulated and can only be disposed at permitted sites, Municipal Solid Wastes (MSW) can be disposed in several ways including household trash bins, curbside receptacles, recycling sites, etc. With increasing sites for and methods of reclaiming certain products, many wastes are partially reused and recycled, but more than half of them by weight go directly to landfills.

1.1.1 Facts about MSW in the USA

According to the annual report conducted by the United States Environmental Protection Agency (EPA), the US generated 250 million tons of MSW in 2008.[2] Although the number has dropped from 254 million tons in 2007 for the first time since 1960, it has tripled since 1960. Considering the 304 million US population, each person generates 4.5 pounds of waste per day.[3] Thirty-three percent of MSW contributes to recycling process, while 54%, or 135 million tons, ends up in landfills. As shown in Figures 1 and 2, paper occupies 33% and plastic counts for 12% of the total MSW, and most of this comes from packaging and containers, which are 30.8% of the total waste.[4] These two materials are the wastes with the highest potential and need for recycling.

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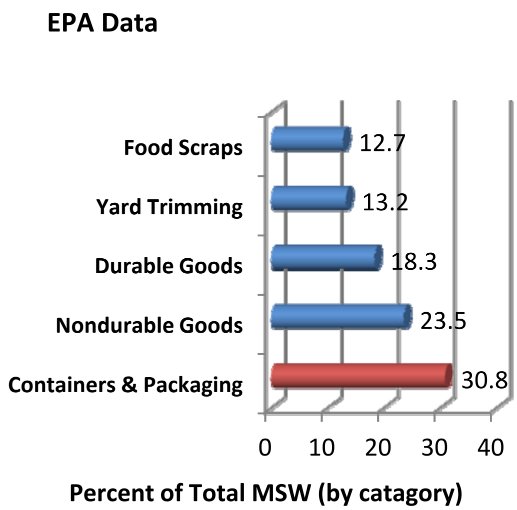
[2] US Environmental Protection Agency, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008," (November 2009): 1, http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2008rpt.pdf (accessed October 3, 2010).
[3] US Environmental Protection Agency, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008," (November 2009): 1, http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2008rpt.pdf (accessed October 3, 2010).
[4] Ibid.



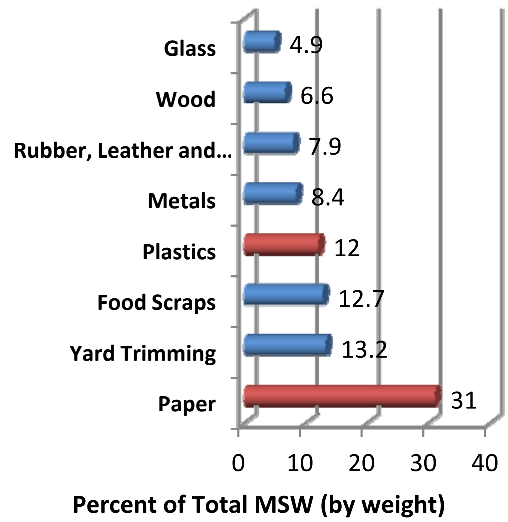


Figure 1 Total MSN Generation (by category), 2008; 250million tons (before recycling)
Figure 2 Total MSW Generation (by material), 2008; 250million tons (before recycling)
Data source: EPA website[5]

According to a report from the EPA, about 2.5 pounds of per capita waste went to landfills in 2008, less than half of the MSW generated in the same year.[6] The US has the highest ratio of recycling in the world, but Germany and the UK only generated about half the total amount as the US.[7] This disposable society flourishes with the culture of speed, and little thought is put into the consequences of throwaway products. Plastic utensils, napkins, food containers, paper, and other products can be easily replaced by reusable goods. Time efficiency has blinded people from seeing long-term environmental impacts. After the mid 20th century, people began to realize the threats of landfills to human living environments. In 1960s, the government started to make effort to control landfills. In 1988, the nation's recycling rate was 12%. In 1998, it had risen to 27%. In 2008, that number was

[5] Ibid.
[6] U.S. Environmental Protection Agency, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008," (November 2009): 10.
[7] Mary H. Cooper, "The Economics of Recycling," The CQ Researcher, Vol 8, March 19, 1998, library.cqpress.com/cqresearcher/getpdf.php?file=cqr19980327.pdf (accessed September 6, 2010).

about 33%.[8] The dramatic increase in the recycling rate is contributed to people's awareness of sustainability and a more systematic recycling process from households to industry. However, because of the limited development of recycling, most paper, plastic, wood, and other materials are only recycled back into the same products by the manufacturer or down-cycled into something less functional and economically efficient.

For example, aluminum containers are recycled back into the same types of products. In 2008, the recycling rate for all aluminum containers and packaging was 36%, which made up 40% of the post-consumer materials used to create the same products.

Meanwhile, there are 15.7 million tons of ferrous materials in MSW, making up 6.3% of the total waste. Steel has a high overall recycled rate at 83% in the US in 2008. This number includes 1.5 million tons of steel containers, which make up 65% of the same type of products. Steel has a relatively higher recycling rate because of the efficient recycling of automobiles. Glass, a material that can be 100% recycled, does not have as high a recycled rate as steel because of its limited reclaiming conditions. In 2008, MSW included 12.2 million tons of glass. Twenty-three percent of it was recycled and was largely composed of drink containers. [9]

1.1.2 MSW and Recycling Facts in Hawaiʻi

Located in the middle of the Pacific Ocean, Hawaiʻi is the most isolated land mass on Earth. Its limited resources and high transportation costs make it difficult for manufacturers to sustain their

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[8] CQ Researcher, "Future of Recycling," CQ Researcher 17 (2007): 1033-60, accessed September 7, 2010, http://library.cqpress.com.eres.library.manoa.hawaii.edu/cqresearcher/getpdf.php?file=cqr20071214C.pdf.
[9] US Environmental Protection Agency, "Glass," United States Environmental Protection Agency, February 24, 2010, accessed September 19, 2010, http://www.epa.gov/osw/conserve/materials/glass.htm.

businesses. Therefore, most of the foods and goods consumed in Hawaiʻi are shipped there from Asia and the mainland as final products. Post-consumer wastes normally go to the landfill, while some of the recyclables are shipped to other places for down-cycling. As landfill areas are limited, there are two alternative methods of handling the waste: Waste-to-Power plants and shipping waste to the mainland.

Until 2008, the City and County of Honolulu alone generated about 1.8 million tons of waste each year that went to landfills.[10] The city houses about 80% of the state's population, but the available area for landfills is limited. Waimanalo Gulch Sanitary Landfill (See Fig. 3), a property of 200 acres, is permitted as the island of Oahu's only MSW landfill until 2012.[11] The relevant state and county departments are still looking for alternative solutions for waste handling after the expiration. In May 2010, a private company planned to ship twenty thousand tons of garbage to Washington for a hundred dollars per ton. In August, the city decided to burn this batch of trash at the H-Power plant instead, trying to solve the waste problems locally. Currently, one-third of the municipal waste is handled by the H-Power plant (see Fig. 4), and a portion of the waste is recycled through governmental programs.[12]

Recycling in Hawaiʻi is more necessary than in probably any other state as it has no options of interstate transportation or ecologically available land for landfills. Only when recycling can be conducted locally will a self-sustaining recycling system be possible.

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[10] Juan Wilson, "Ea O Ka Aina: Hawaii Garbage Crisis," Ea O Ka Aina, August 24, 2010, http://islandbreath.blogspot.com/2010/08/hawaii-garbage-crisis.html (accessed November 25, 2010).
[11] "Waimanalo Gulch Sanitary Landfill Expansion Fact Sheet," *Department of Environmental Service,* www.opala.org/pdfs/solid_waste/WGSL_Factsheet.pdf (accessed November 9, 2010).
[12] Michael Cooper, "Packed and Ready to Go in Hawaii - 20,000 Tons of Garbage," The New York Times, May 22, 2010, http://www.nytimes.com/2010/05/23/us/23garbage.html?_r=1 (accessed November 25, 2010).


Figure 3 Waimanalo Gulch Sanitary Landfill paving, Honolulu, November 17, 2011 (Photo source: author)
Figure 4 City and County of Honolulu H-Power Plant Burner, November 17, 2011 (Photo source: author)

1.1.3 Plastic Threats to Hawaiʻi

Another severe indicator of failed waste management, especially of plastic waste, is the "plastic soup" that is floating on both sides of the Hawaiian Islands. The garbage patch was discovered by American oceanographer Charles Moore in the north Pacific Ocean, between California and Hawaiʻi and between Hawaiʻi and Japan (see Fig. 5); it consists of over a hundred million tons of floating wastes.[13] Data has shown that the impacted area is bigger than the size of the United States, and the area between Hawaiʻi and California is twice the size as Texas.[14]

The patch was caused mainly by two things: the non-biodegradability of plastic and insufficient management of ocean waste. The garbage patch is primarily composed of plastic waste from decades ago. The waste comes from both waste streams from land and disposal in the ocean.[15] Flushed to the ocean along rivers and streams, the trash originally included all kinds of wastes, but most of the

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[13] "The world's rubbish dump: a tip that stretches from Hawaii to Japan," The Independent, February 5, 2008, http://www.independent.co.uk/environment/the-worlds-rubbish-dump-a-garbage-tip-that-stretches-from-hawaii-to-japan-778016.html (accessed November 16, 2010).
[14] Tom Mosakowski, "Plastic Waste is Turning the North Pacific Ocean Into a Garbage Dump," Natural News, March 25, 2008, http://www.naturalnews.com/022885.html (accessed December 9, 2010).
[15] Ibid.

debris, such as wood and cotton, biodegraded in the water. However, plastic, which has been used increasingly in recent decades, is not biodegradable, and remains in the water and slowly amasses through the activation of oceanic gyre. Despite the fact that plastic breaks down into smaller pieces, it is not likely to disappear in the coming decades. According to Tom Mosakowski, the citizen journailist of the Natural News, pieces of plastics from fifty years ago are still in the ocean.[16] Therefore, the garbage patch in the ocean only started to form in the past decade. In the coming chapter, the harmful result of the plastic pieces floating in the ocean will be discussed.

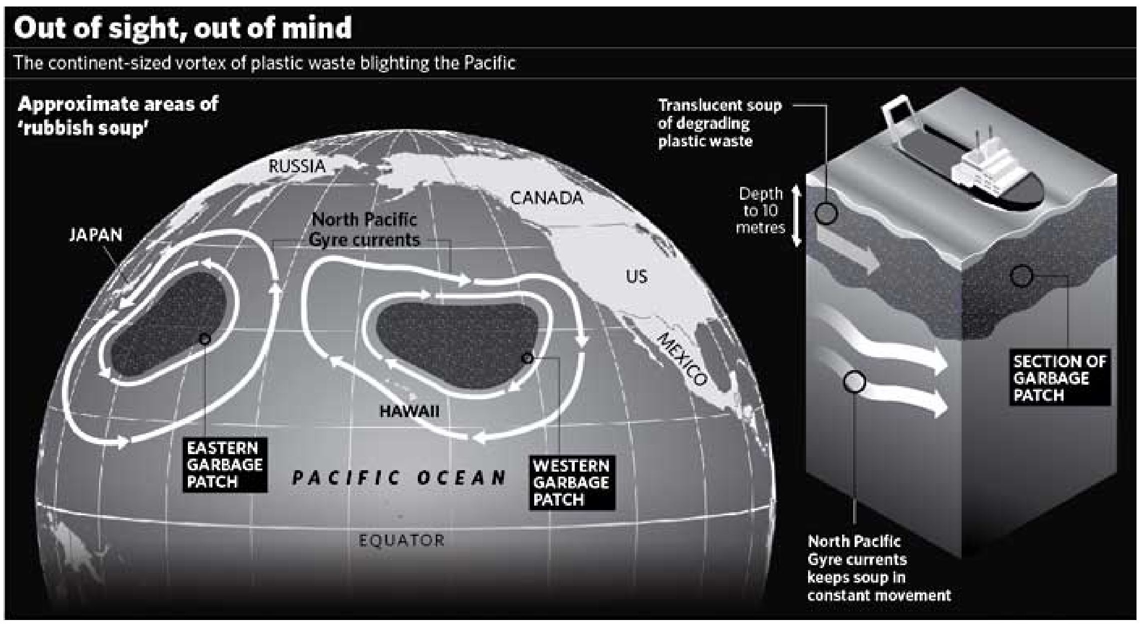

Figure 5. The Plastic Soup[17]

Mosakowski pointed out that 10% of plastic waste is washed from the land to the ocean, where most of it ends up at the bottom of the ocean. However, about 30% of the waste becomes a part of the patch.[18] The patch will continue to grow if there is no effective resolution to reduce plastic disposal.

[16] Tom Mosakowski, "Plastic Waste is Turning the North Pacific Ocean Into a Garbage Dump," Natural News, March 25, 2008, http://www.naturalnews.com/022885.html (accessed December 9, 2010).
[17] Source: Image from the Independent, 2008.
[18] Ibid.

Chris Parry from the California Coastal Commission in San Francisco states that the consumption of plastic must be reduced, but the current dependence on synthetic materials is not likely to allow that to happen.

The trash has the greatest impacts on the shorelines of California and the islands of Hawaiʻi. While Hawaiʻi is characterized as paradise for its well preserved natural scenery, this accumulative waste patch will deeply influence the ecosystem around the islands as turtles, fish, coral, and other marine organisms share their home with a pile of toxic waste. The result will not only affect ocean animals, but may also harm public health and the economy. There is a concern that this toxic waste may pollute the beach water, which has direct contact with tourists from all over the world. The contamination, therefore, may travel to other parts of the world with these visitors.

The patch will cost billions of dollars to remove. The enormous figure may sound daunting, but it may be solved through political or economic actions. It may take years, but it is a solid number. What scientists are most worried about is where the waste will go after it is scooped out of the water.[19] In addition to a storage area for the waste, new technologies are needed to help reduce the world's ecological footprint.

1.1.4 Recycling Efforts in Hawaiʻi

Hawaiʻi has been trying to find new ways to divert waste from the waste stream. About five years ago, the government began funding the recycling programs in Hawaiʻi. The government spent millions of dollars to set up recycling bins in each house, condo building, business building and school to encourage people to drop off recyclable waste at the categorized bins. The programs have significantly

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[19] Tom Mosakowski, "Plastic Waste is Turning the North Pacific Ocean Into a Garbage Dump," Natural News, March 25, 2008, http://www.naturalnews.com/022885.html (accessed December 9, 2010).

improved recycling rates in the islands. However, the current programs still have plenty of limitations, which need to be lessened to achieve a higher efficiency and effectiveness.

❖ Hi-5 Reclamation Program

For the past five years, the Hi-5 recycling program has successfully achieved a rate of two-thirds out of the 900 million bottles purchased in Hawaiʻi per year. Meanwhile, the City and County of Honolulu has been providing recycling services through the three colored recycling bins at each house, community recycling bins, and curbside recycling services to reclaim recyclable refuse. The recycling programs are getting more widely recognized and utilized; however, the majority of recyclable materials are still not dealt with efficiently.

One of the examples is the plastic bottles excluded from the Hi-5 program like milk jugs and laundry detergent containers. These containers are made of Type 2 plastic, which is in high demand in the construction industry.

The reclamation centers (see Fig. 6 & 7), work with the government program as a contractor. They collect, sort, and bale the waste for further handling, which is mostly shipped to other places. These recycling centers accept a very small selection of materials, especially bottles. The bottle types excluded from the Hi-5 program will not be accepted by the recycling centers. Therefore, hundreds of HDPE bottles are delivered to the waste stream every day.

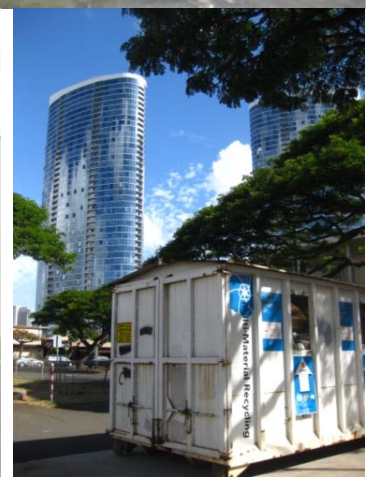

Figure 6 & 7 Manual sorting, Reynolds Recycling Center, September 26, 2011
Figure 8 Reynolds Recycling reclamation spot at Kapolei Shopping Center, November 17, 2011
Figure 9 Community Recycling Bin, Honolulu, September 17, 2011
(Photo source: author)

6	7
8	9

❖ Recycling Pick-up

Since the three colored bins arrived at each residential unit, the curbside pick-up recycling program has been doing an incredible job. The bins increased the convenience and awareness of recycling and thus increased the recycling rate. The curbside recycling bins even compete with the community recycling bins, which have been in place since the 1990s. The private bins for condos and schools may slowly replace the community bins (see Fig. 9), which will improve efficiency.

According to Adam Bien, a Recycling Specialist of the City and County of Honolulu, the city is working with schools to establish a self-responsible recycling system.[20] In the near future, schools will have a more effective recycling system that services the entire school without governmental programs. Although the community recycling bins will be removed from schools, the recycling rate is expected to rise. Education and a convenient recycling system are critical to increase awareness.

❖ H-Power Plant

The H-Power (Honolulu Project of Waste and Energy Recovery) program creates electricity by burning municipal waste. It dramatically reduces the waste that goes into landfills, and it fulfills about 7% of the electricity demands of the island. According to Suzanne Jones, the Recycling Coordinator of City and County of Honolulu, the reclaimed plastics are divided into two categories: recycled and combustible. The PET and HDPE are shipped to China for their higher value compared to other plastics. However, the rest is thrown into a furnace to produce power. Most of the plastics are not easily combustible, but when they burn, they obtain a high BTU value due to their petroleum base. The same goes for other recycled waste; the categories with higher values are diverted to the recycling process while the rest goes into the furnace.[21]

However, the recyclers, hired as contractors, have a different perspective. Anything combustible is welcome at the H-Power plant, says Jones, and they would love to throw everything in the furnace. This leads to a constant debate between the city recycling department and the recyclers about what should be recycled back into consumer products.

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[20] Adam Bien, interview by author, phone interview, Honolulu, September 28, 2011.
[21] Suzanne Jones, Interview by author, Phone interview, Honolulu, September 28, 2011.

Evaluations are conducted periodically to balance the advantages and limitations of using the waste as a substitute for fossil fuel or a replacement of certain raw materials.

By 2013, the city expects to divert 70% of the waste from landfill, and a new facility will be built by 2012. There is a tendency for the City and County of Honolulu to increase the ratio of diverted landfill as H-Power fuel, which means the waste with lower values may end up being burnt. However, in order to reduce the carbon footprint on the environment and to reduce the embodied energy of the products, it is more efficient to handle the waste by reforming the post-consumer objects into a new product. After all, it is easier to find a substitute fuel source than a specific product ingredient.


Figure 10 Waste pushed onto delivery belt;
Figure 11 Waste sorted and delivered through the belt;
Figure 12 Waste delivered from the sorting facility to the burners through a bridge, Honolulu H-Power Plant, November 17, 2011(Photo source: author)

1.2 The Restrictions of the Recycling Industry in Hawaiʻi

Back in the 1960s, recycling was a popular topic for progressive groups. However, it has been only a secondary subject for people with artistic talents and imagination. This trend of recycling does not focus on the viability and functionality of the outcomes, so a limited audience is inspired and influenced. As sustainability becomes more and more popular, recycling becomes widespread and common. Governmental and private efforts have called for attention to recycling, but many businesses do not find it feasible for various reasons. Nevertheless, an increasing number of industries have utilized waste to create a unique business.

In the recent decade, recycling has become much more popular, not only because of the rising price of raw materials, but also due to the growing recognition of the need to reduce our ecological footprint. However, the establishment of a relatively comprehensive recycling system is time-consuming. The major arguments against recycling are energy consumption, cost, and the complexity of the recycling process.[22]

Figure 13 Plastic Milk Containers[23]

Although awareness of the need for environmental protection has increased in recent decades, the economic benefit is still the largest factor in deciding whether the idea is adoptable. "In the mainland, some cities have decided to stop curbside recycling because of the high cost…the economy is down…would people use their tax to pay for recycling or police?" states Bruce Iverson, Director of

[22] Mary H. Cooper, 1998.
[23] "96% of Milk jugs are able to be recycled," Recycling RecoveryTTA, http://recoverytta.blogspot.com/ (accessed December 1, 2010).

Marketing for Reynolds Recycling Inc. in Honolulu.[24] He explains that the bottles collected at the redemption sites will be gathered and sold to the mainland, mainly California, and Asia, where they will be made into carpet, clothing, and fiber. He agrees with the increasing local attention and efforts to recycle. However, it is still difficult for a full-service recycling business in Hawai'i, as the state is dependent on world prices for materials, not to mention the unstable supply of reclaimed materials.[25]

The Aloha Plastic Recycling Inc. (APR) is an appropriate example. As the only recycling company in Hawai'i, the APR recycled #2 plastic bottles, which were extruded into plastic lumber for constructional use. However, the unstable and limited reclaimed resources drove the company to buy new plastic materials from across the Pacific Ocean.[26] This decision moved away from the initial intention to turn waste into sustainable products, and it dramatically reduced the financial viability of the company. Eventually, the company found it too hard to sustain the business and closed down.

Jaqueline Simone Ambrose, a Project Manager of Aloha Shares Network, Maui Recycling Group, was a former employee at the APR. In a phone interview, she seemed disappointed by some businesses who claim to be sustainable in small manners while being some of the bigger pollution producers. "They throw away thousands of milk containers (see Fig. 13) every year," says Ambrose.[27] She believes that a successful business should care about the people and the earth in addition to company profits. Maui County has offered reclaiming services for some businesses that can provide huge amounts of stable recyclables annually; however, businesses do not simply nod their heads and sign.[28] According to Iverson, the reclaiming services may involve some legal revision depending on the company's policies, or in the case of the milk company, may involve extra taxes; there can be

[24] Bruce Iverson, telephone interviewed by author, Honolulu, Hawaii, November 16, 2010.
[25] Ibid.
[26] Bruce Iverson, 2010.
[27] Jaqueline S. Ambrose, telephone interviewed by author, November 8, 2010.
[28] Ibid.

many reasons why certain businesses find it difficult to sign a reclaiming agreement without risking the company's benefits.[29]

In addition to the challenge of obtaining stable resources, the sorting process also limits recycling. Iverson emphasizes that sorting and handling are the most difficult and expensive stages. Workers stand along the delivering belt and manually separate different types of waste. In many cases, the recyclables are broken or contaminated. When glass is broken into pieces, not only is it dangerous for the sorting workers, it may also contaminate or damage other wastes. "When the recyclables have unusual defects, no one wants to buy it because it takes more work to clean it up, or they will pay for a very low price," says Iverson.[30] Looking at different recycling websites, one can see clear divisions between different types of plastic based on color, transparency, size, and so on. The sorting load will be either on the households or, more likely, the recycling agencies.

Vannessa Goodship, the author of *Introduction of Plastics Recycling*, outlines "legislation, market forces, and environmental pressure" as the three major factors in recycling.[31] Out of these, only environmental pressure is commonly recognized. Nevertheless, more and more designers are paying attention to alternative uses for recycled materials, and the cross-field application of these materials inspires an expanded market for them.

Applying municipal recycled materials in a living environment not only reduces waste and conserves raw materials, but also implants the idea of recycling into the public's subconscious. Recycled plastic materials in construction constantly remind people of the opportunities to turn waste into something we need to improve our options and quality of living. Each of these items embraces a huge market potential, and each has infinite potential for design creativity.

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[29] Bruce Iverson, 2010.
[30] Ibid.
[31] Goodship, Vannessa. *Introduction to Plastics Recycling - Second Edition*. 2Rev Ed. N.C.: Smithers Rapra Technology, 2007.

1.3 A Brief Introduction to Plastics

Compared to other materials, plastic is a young material, but it has been widely used all over the world. There are three people who have made significant contributions in plastic inventions. In 1830s, a natural polymer type of plastic—rubber—was discovered by Charles Goodyear, and it called attention to synthetic products. In 1844, Alexander Parkes created a plastic that was made from cellulose, which can be shaped via heating and cooling processes. This lightweight material was intended to be manufactured to replace rubber; however, the production costs were too high for this cheaper material. Leo Baekeland invented the entirely synthetic plastic in 1907, and the material was soon applied in the construction industry, like insulation and wood additives, for its outstanding properties, such as water and chemical resistance, stiffness, etc.[32] Since then, plastic development has entered a new era and become an expanding family.

All plastics can be grouped into two major categories based on their thermal reaction: thermoplastic and thermoset plastic. Thermoplastic is the most common type of plastic we normally use. It is made of melted plastic pellets and shaped through heating and cooling processes. This category is used in the majority of the products people use daily, and it includes polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC). Reinforcement is not necessary for thermoplastics, and they can be formed into any shape to adjust to different applications. On the other hand, thermoset plastic is more thermally stable because it is made through a chemical reaction. It has better durability, but is mostly unrecyclable. Once it settles, it cannot be turned back into a fluid form. This type of product includes paint, glue, and coating, as well as cross-linked polyethylene

[32] Victoria Ballard Bell and Patrick Rand, Materials for Architectural Design (London: Laurence King Publishing, 2006) 219.

(XLPE or PEX) piping.[33] Both of these categories of plastic are commonly used in daily life, and they are composed of various types of plastics with different chemical structures and densities.

Since the mid-twentieth century, plastic has been used extensively in the architectural field to explore unconventional construction and structures such as curving walls, tensile structures, and membranous building envelopes.

1.3.1 Resin Identification Codes

The vast variety of plastic comes from its synthetic nature. Extracted from natural gas and crude oil, a monomer—the structural unit of plastic—is combined with different monomers to form a new type.[34] Therefore, each type of synthetic has its own characteristics in addition to the common general properties.

The Resin Codes are based on one fundamental principle of plastic recycling: homogeneity. Since plastic needs a combination of different components to achieve its most suitable property for each application, it is almost impossible to require pure material in recycling process. However, when the components of a mixture are stable and consistent, the mixture is considered one new recovered raw material that obtains unique properties.[35] The consistency benefits all aspects of the product: ease of reclaiming, established knowledge of the material properties, efficiency in the repetitive production process, and reduced mistakes and material waste. Generally, plastics are divided into seven categories in the Resin Identification Codes developed by the Society of the Plastic Industry (SPI) in 1988 (see Fig. 14). These codes are formed into the plastic as an identifier.

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[33] Meg Calkins, 374.
[34] Victoria Ballard Bell and Patrick Rand, 219.
[35] Vannessa Goodship, Introduction to Plastics Recycling - Second Edition, 2Rev Ed, New York: Smithers Rapra Technology, 2007, 48.

Figure 14 Resin Identification Codes[36]
Figure 15 7 Categories of Plastics[37]

- **Seven Types of Plastics**

Type 1 plastic is Polyethylene Terephthalate (PETE/PET). It is commonly used to produce soft drink, juice, and peanut butter bottles and jars, and so on. It has chemical stability and has been proven safe for food. Because recycling programs for these products are common, PETE has a higher recycling rate than other plastic types.

HDPE is commonly used and desired in constructional applications. The production of HDPE does not require toxic chemicals for stabilization. However, the fireproof additives may bring harmful elements into the material.[38] This material will be discussed further in a later section.

Type 4 plastic or Low Density Polyethylene (LDPE), is commonly used for grocery bags, frozen food bags, trash can liners, and so on. LDPE has similar properties to HDPE. It also has high strength, which allows it to carry objects hundreds of times heavier than the bag itself. Its chemical stability has also been proven, so it is commonly used for food.

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[36] *Source:* Data from Plastic & Rubber Machinery Marketplace, "What are Resin Identification Codes for Plastic Recycling, Plastic Identification Code," Plastic & Rubber Machinery Marketplace, http://www.plasticrubbermachines.com/articles/plastic-id-codes.html (accessed October 6, 2010).
[37] Brian Clark Howard, "Recycling Symbols on Plastics," The Daily Green, http://www.thedailygreen.com/green-homes/latest/recycling-symbols-plastics-460321 (accessed November 23, 2011).
[38] Meg Calkins, *393.*

Type 5 plastic, Polypropylene (PP), is one of the lightest plastics, which is also commonly used for food containers. It also has a relatively high melting point, making it resistant to hot water and preventing harmful objects from being released into the food.[39]

Type 6 plastic, Polystyrene (PS), is commonly used for takeout containers, single-use disposable cups, foam insulation, and so on. This plastic is stable in regular conditions, but is toxic when burning and inhalation can affect the reproductive system. This material is non-recyclable; therefore, the use of PS has been banned in some places.

Type 7 is generally a mixture of several types of plastic that fail to fall within the six types above. While each component may be recyclable, the energy and cost of dividing them are far more than those required to create the materials from raw resources. Therefore, it is normally considered non-recyclable.

There are several types of plastic commonly used in construction sites, including HDPE, LDPE, LLDPE, XLPE, PP, PVC, PS, and ABS.[40] However, most of them are used for supporting features like pipelines, carport panels, and so on.

1.3.2 Recycling Rate of Plastic in MSW

The recycling of plastic is one of the biggest environmental challenges. Meanwhile, it is also the biggest marketing opportunity for the spread of plastic adoptability. Plastic should be renowned for its incredible potential, instead of being restricted for its fatal impacts on the environment.

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[39] "What is Polypropylene?" wiseGEEK: clear answers for common questions, http://www.wisegeek.com/what-is-polypropylene.htm (accessed November 22, 2010).
[40] Meg Calkins, *373.*

Currently, plastic recycling is weak and unstable. Partially because of the lack of market, the recycling industry is facing many technical and technological challenges. While the waste stream is widely available, its variety also becomes a barrier due to the difficulties of categorization and sorting. Composite items add to the difficulties in recycling.

There are three major categories of products made from plastic. The biggest category is containers and packaging, but only 13% of them were recycled in 2008, and this was the highest recycling rate among all plastic products.[41] The recycling process for this type of waste is also closed-loop, and the containers are turned back into new containers.

The second category of plastic MSW is appliances and furniture, and after that, it is plastic bags, utensils, cups, etc. In the worsening disposable culture of America and the world, the extremely high formability of plastic has been degraded by the short-term usage of a product that costs more environmentally and requires energy. In addition to reducing wastes, increasing recycling is also an urgent mission.

Following paper, plastic is the second largest waste besides yard trimmings and food scraps. In 2008, 30 million tons of plastic MSW were generated, equaling 12% by total weight. Back in the 1960s, the amount of plastic was as low as 1%. Since that time, the usage and disposal of this material has been rapidly growing.[42] In 2005, western Europe produced about 40 million tons of plastic; this is only 10 million tons more than the MSW in America alone. While the consumption of plastic is rising dramatically, recycling is also increasing. However, the energy and resources it takes to reclaim, sort, and reproduce plastic limits its recycling.

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[41] US Environmental Protection Agency, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008," (November 2009): 8, http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2008rpt.pdf (accessed October 3, 2010).
[42] US Environmental Protection Agency, "Plastics," http://www.epa.gov/osw/conserve/materials/plastics.htm (accessed September 16, 2010).

1.3.3 Advantages of Plastics

Plastics became popular because of their durability. They require less maintenance than many other materials. They do not rot due to weather or termites nor do they rust like metal. Its waterproof and self-cleaning characteristics also help plastic to stabilize its market in all fields. Moreover, plastics are widely used because they are lightweight and diverse. The properties of plastic change with the chemical structure. Its flexibility in density and bonding allow plastic to be made into any product. It can achieve a range of thickness, transparency, and stiffness, providing an extensive pool of materials for functional and efficient application. For example, polycarbonate sheets have been used frequently used to replace heavy glass planes. Not only is plastic lightweight, making it cheaper to transport and more convenient for construction, but it is also more cost and energy efficient to obtain various textures and appearances by adding various additives.

Additives are components that can improve the suitability of plastic in product applications. There are thousands of additives available; the most common are for reduction of degradability and improvement of strength, temperature tolerance, and appearance. Various objects can also be embedded in plastic to provide specific textures that no other materials can provide.

1.3.4 Environmental Pollution of Plastic Wastes

The biggest concern in the reuse of plastic is not raw materials nor embodied energy, but the environmental impacts. Plastic is also known for its durability—which means its lack of biodegradability. The hidden threats of plastics exist in both landfills and the ocean. Plastic is known to be hazardous when toxic chemicals are released during processing, heating, and even break down in the water or earth.

Plastics take centuries to degrade. In the ocean, this results in piles of waste along shorelines and ecological harm. Plastics often contain chemicals that are commonly carcinogenic or that can lead to other serious diseases.

In 2008, scientists discovered the "magnetic" nature of plastics in water, which collect other toxic chemicals, so the plastic itself can be a thousand times more toxic than the water around it.[43] While the plastics attract toxic chemicals naturally, turtles, jellyfish, and many species of fish mistakenly eat plastic bags and other products. Sadly, they have no idea how much poison enters their bodies with these "magnets." If these marine animals are captured and eaten by humans, the humans may be affected too.

Marine pollution is one of the biggest concerns in plastic disposal. Japanese scientist Katsuhiko Sido has taken samples from different countries and proven that plastics do not necessarily take hundreds of years to break down. In fact, some of them can break down within a year in the water.[44] However, the toxic components are released in the water, making what Sido describes as a "pot of toxic soup."

The same kinds of toxins are also released during the break down of plastic in landfills. As shown above, whether or not the plastic degrades, it is a threat to the environment as long as there is a release of the poison chemicals.

Plastic is a material that people love and hate. It is a relatively young invention, and it has so much more potential for human exploration and use. Plastic has infiltrated daily life and become a necessity, which is not easily replaced or eliminated. To further spread the advantages of plastic without

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[43] David Shukman, "Warning on plastic's toxic threat," BBC News – Home, March 27, 2008, http://news.bbc.co.uk/2/hi/science/nature/7316441.stm (accessed October 20, 2010).
[44] Carolyn Barry, "Plastic Breaks Down in Ocean, After All - And Fast," National Geographic News, August 20, 2009, http://news.nationalgeographic.com/news/2009/08/090820-plastic-decomposes-oceans-seas.html (accessed October 20, 2010).

bringing harm to the environment, in any industry, the only solution is a carefully established system and legislation of recycling and reuse.

Figure 16 Sea bird starved to death after eating 1600 pieces of plastic[45]

Conclusion

There is a severe need of plastic recycling to prevent environmental pollution and increase the effective use of raw resources, especially Hawaiʻi and other isolated regions. The expansion of plastic recycling meets difficulty because the existing development does not meet the waste production rate. To increase the efficiency and feasibility of plastic recycling, the recycled products need to jump out of the closed loop, and start considering new products that increase the value and function of the material, in order to increase the recycling rate of the wastes.

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45 "Floating trash-berg bigger than Texas found in the Pacific," Cassiopaea, October 19, 2006, http://www.cassiopaea.org/forum/index.php?topic=3737.0 (accessed November 15, 2010).

Chapter 2 Upcycling in Three Recycling Methods

The development of recycling processing has been evolving. It has slowly moved beyond solely recycling and reached the stage where post-consumer waste is no longer used as a secondary resource. Instead of just an alternative, the recycled materials present a range of unique characteristics that surpass the conventional materials. Capturing these features is an exciting assignment for the designers, who creatively apply the recycled materials in a reasonable way.

There are three main recycling methods: reuse, mechanical recycling, and feedstock recycling. The first two methods are commonly used to preserve and present the material capabilities. Though there are challenges and restrictions, a great amount of designs have proved the potentials of recycled materials. This chapter shows a series of selective case studies that achieved the inspirational applications of paper, plastic, and composite.

2.1 Upcycling

According to McDonough and Braungart, the authors of *Cradle to Cradle: Remaking the Way We Make Things*,[46] upcycling means "the practice of taking something that is disposable and transforming it into something of greater uses and value." This definition is in contrast to loop-cycling, or worse, downcycling. Beyond the economic benefits, more efficient utilization of raw material is an important reason for transforming trash into "value added" products that may have a higher value than its post-consumer value, so that the use of material is not limited to the hierarchical relationship between the original and the recycled.

2.1.1 Increased Value of Recycled Product

The value of a product is not only determined by its price, but also the ecological footprint of its lifecycle. The embodied energy consumed throughout the whole life of a recycled product is the criteria with which to decide whether the product is worth the recycling process or better used as fuel.

In addition to the increase in product value, finding a new form of a product is an exciting aspect of the upcycling challenge. Upcycling tries to avoid recycling the product back to a similar product, which is instead reformed into a seemingly brand new item. Even better, in this new form, the product provides new functions after upcycling.

The methods used to recycle plastics directly affect the application of the recycled materials and their functions. The three major recycling categories—reuse, mechanical, and chemical—have different complexities. Energy consumption, required technology, and technical issues vary during the recycling process. These varieties may reflect on the final products used, for example, in buildings.

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[46] William McDonough and Michael Braungart, *Cradle to cradle: remaking the way we make things*, New York: North Point Press, 2002.

This chapter talks about the three types of recycling methods. Different reused and recycled materials are discussed to find a balance in the complexity of product processing and construction.

Plastic plays an important role in everyday living, and thus has a high potential for upcycling. Food packaging makes up the largest percentage of plastic products, but in this case, closed-loop recycling proves to be the most efficient production method. Meanwhile, the building and construction sector is the second largest consumer of plastics, and it is still growing. Therefore, the development of upcycling is crucial in the building and construction sector. The recycled products should ideally present the characteristics and improve the weaknesses of the original material.

2.1.2 The Role of Design in Recycling

Design is a means of spreading a new model of living that represents changing contexts in terms of technology, environmental responsibility, psychology, and economy. It aims to find a balance between solutions for current issues and a futuristic vision of quality living. Design using alternative materials is the key to connecting these two factors.

The design process is also a problem solving process. For stubborn existing problems, the

The design in this thesis is focused on municipal recycled materials and has two goals. The main goal is to discover innovative applications of existing materials to create a new living experience for people. The second goal is to spread the message of recycling by demonstrating recycled material use in the fundamental element of living—the home.

The project does not aim to invent new materials or structural systems that require advanced investigation and technology. Instead, it tries to discover existing qualities of materials and to resolve the limitations of these materials in construction use. Not only do these materials provide new options for building components, they also embrace different properties that can achieve more functions with fewer components.

The process of discovering new ways to utilize a material is a good chance for people to improve the functions of a conventional product as well. Many alternative materials fulfill more than one function, and they have great potential to replace more than one material in construction, thus reducing shipping costs, material amounts, environmental impacts, etc. Also, the specific structure of each alternative material provides physical properties that allow different spatial experiences like light-transmission, color, texture, stiffness, and so on.

Besides the aesthetics and functions of the product, a design should also reflect the change of time.

2.2 Reuse

The reuse of post-consumer products, which is also called minimal recycling, includes original purpose and new application of the material. It can be cut, folded, or grouped, but the original material components remain the same. Reuse is recommended rather than recycling because it can conserve energy, reduce pollution, and increase cost efficiency, etc. This process involves few technological requirements because sorting and handling is the most complex process. The application of reused material involves more thought in terms of construction methods; meanwhile, it allows more room for innovative design compared to other manufactured recycled products.

2.2.1 Case Study: Sustainable Form-Inclusion System (SFIS), SOM, 2009

Skidmore, Owings & Merrill LLI (SOM) intends to reuse plastic wastes directly in building construction. The product they developed aims to create a model that reduces waste, resource and energy consumption in construction, and greenhouse gas emissions. SOM proposes to replace partial concrete casting with empty water bottles, plastic bags, tires, and so on.[47] This process, if calculated and examined carefully, is one of the most simple but practical reuse methods.

As one of most influential companies in the field, SOM has been emphasizing self-renewal by constantly updating its internal technology and skills.[48] In an interview with the electronic magazine *Arch Daily*, Craig Hartman, a design partner of San Francisco SOM, pointed out that architects should think beyond architecture.[49] The firm's global vision and environmental awareness led to its attention to plastic wastes and their application in the building industry. Unlike many other applications, the Sustainable Form-Inclusion System (SFIS) targets purely recycled bottles and the conservation of resources.

❖ Material

The PET bottles and plastic bags in the SFIS are widely used, but they are new materials in building use. Polyethylene terephthalate (PET) typically has suitable properties for construction use including its light weight, stiffness, chemical stabilization, low water-absorption, and gas barrier and self-distinguishing properties.[50] [51] To create a controllable bubble in the concrete slab, these bottles are reused with their caps.[52] These qualities may provide stability in the construction process and high durability during the building's life.

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[47] Skidmore, Owings & Merrill LLP,"SOM Awarded Four R&D Awards By Architect Magazine," SOM.com, http://www.som.com/content.cfm/82709_som_wins_4_r+d_awards (accessed November 15, 2010).
[48] Basulto, David," AD Interviews: Craig Hartman/SOM," Arch Daily, August 26, 2009, www.archdaily.com/33309/ad-interviews-craig-hartman-som/ (accessed December 2, 2010).
[49] Basulto, David, 2009.
[50] AZoM™.com Pty.Ltd, "Polyethylene Terephthalate Polyester (PET, PETP) – Properties and Applications – Supplier Data by Goodfellow," AZoM™ - The A to Z of Materials and AZojomo, http://www.azom.com/details.asp?ArticleID=2047 (accessed December 5, 2010).
[51] "PET bottles," designboom, http://www.designboom.com/contemporary/petbottles.html (accessed December 5, 2010).
[52] Amanda Kolson Hurley, "Sustainable Form-Inclusion System," Architect Magazine, August 10, 2009, http://www.architectmagazine.com/green-technology/sustainable-form-inclusion-system.aspx (accessed November 15, 2010).

However, the stiffness of PET bottles is much lower than normal structural elements of a building. The SFIS utilizes the vertical strength of the bottles and resolves their lateral flexibility by grouping them together.

The SFIS is one of the most efficient forms of reuse. The bottles are kept in their original form with the caps and wrapping paper on. These bottles can be easily collected, and do not need to undergo color sorting and cap removal. The "non-corporate approach," described by Craig Hodgetts, a jury member of the 2009 R+D Awards, has effectively eliminated the energy and cost of shipping and manufacturing.[53] However, it requires a cleaner bottle surface to ensure the purity of concrete slabs. Also, the bottles should remain intact to maximize air tightness and consistent air volume.

❖ **Construction method**

The SFIS is designed for conventional slab and beam systems, and is meant to partially replace concrete in the framed floor.[54] The system aims to use fewer materials with the same level of performance. The bottles are bundled together and placed in the formwork of concrete slab.[55] SOM has proposed a layout for the bundled bottles. Figure 17 shows the various densities of the SFIS according to the gradient of structural performance. Location A, in the center of the dashed rectangle, has the densest SFIS. These bubbles are used to reduce the weight in the center of the grid to coordinate the bigger bending moment and smaller shear force in other parts. Comparatively, B has less SFIS, and C, which is located around the columns, has the least because it needs the most strength among the three types of areas.

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[53] Amanda Kolson Hurley, "Sustainable Form-Inclusion System," Architect Magazine, August 10, 2009, http://www.architectmagazine.com/green-technology/sustainable-form-inclusion-system.aspx (accessed November 15, 2010).
[54] Skidmore, Owings & Merrill LLP,"SOM Awarded Four R&D Awards By Architect Magazine," SOM.com, http://www.som.com/content.cfm/82709_som_wins_4_r+d_awards (accessed November 15, 2010).
[55] Amanda Kolson Hurley, 2009.

The bottles are tied with the rebar to secure their locations. When concrete is poured around the bottles, the pressure will only have limited impacts on the air volume in the bottle.[56] Figure 19 shows the sections of two arrangement methods. The bottles are tied between the two layers of horizontal rebar. The bottles are kept in their original shapes to maximize their air space and allow a greater reduction of building weight.[57]

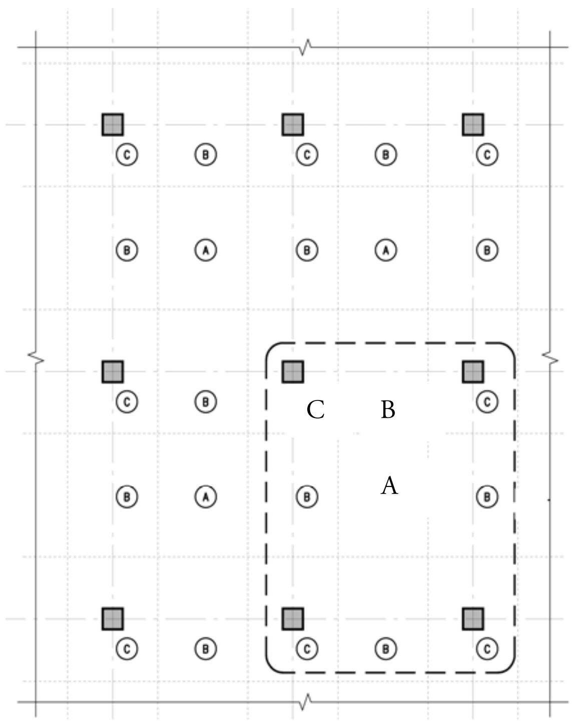

Figure 17. SFIS layout in plan view[58]
Figure 18. SFIS tied with rebar[59]

The SFIS not only replaces some concrete materials, but it also lessens the demand for rebar. Energy consumption and CO^2 emissions are reduced in a series of processes, from recycling, shipping, and manufacturing, to construction. SOM suggests that this system reduces the material amounts in the superstructure and foundation by up to 35%.[60] However, this system requires precise professional analysis to ensure the required structural strength and fire endurance. Also, the bottles cannot be baled to reduce shipping costs.

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[56] Amanda Kolson Hurley, 2009.
[57] Ibid.
[58] Amanda Kolson Hurley, 2009.
[59] Source: Image from Skidmore, Owings & Merrill LLP, 2009.
[60] Skidmore, Owings & Merrill LLP,"SOM Awarded Four R&D Awards by Architect Magazine," SOM.com, http://www.som.com/content.cfm/82709_som_wins_4_r+d_awards (accessed November 15, 2010).

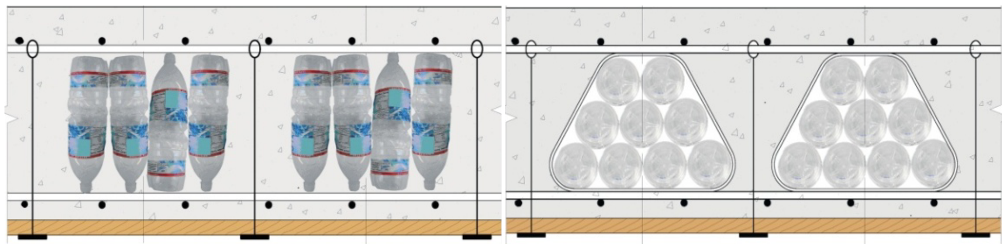

Figure 19. Two of the placements of the SFIS in concrete slab[61]

The SFIS utilizes handy and low-tech methods to apply reused materials to structural use by professional engineering calculations. The applicability of this recycling method has the potential to extend to other waste which has a low density and water absorption. Although this specific system belongs to SOM, the principles behind it announced the possibility of integrating plastic into conventional materials that traditionally seem incompatible. The simple but practical application of the SFIS represents the possibility of achieving less for more.

2.2.2 Case Study: Lighting Fixtures Made of Reused Bottles, Europe

The light-transmitting character of plastic bottles encourages creative designs for lamps, shading devices, dividers, and so on. Designers can utilize the various forms and colors of different kinds of bottles to create a combination of function and aesthetics. The pattern and curvature of each part of a plastic bottle can inspire designers to create new patterns and textures, bringing a mysterious but joyful sense to a space.

For example, the UFO lamp made by Heath Nash (see Fig. 20) utilizes the handles from dozens of milk bottles to form a new pattern by unfolding and configuring the pieces.[62] The shading from the curvature and the light values from the layers create the rich sense of a three-dimensional flower. The

[61] Source: Image from Skidmore, Owings & Merrill LLP, 2009.
[62] Heath Nash, "Heath Nash," Heath Nash makes cool things, http://www.heathnash.com/others.php (accessed August 1, 2011).

flexibility, durability, and heat resistance of milk bottles allow for potential upcycling. One milk bottle costs about one dollar, but a nicely crafted lamp can be worth hundreds of dollars. The creativity that utilizes the advantages of the waste and transforms it into a valuable product is priceless.

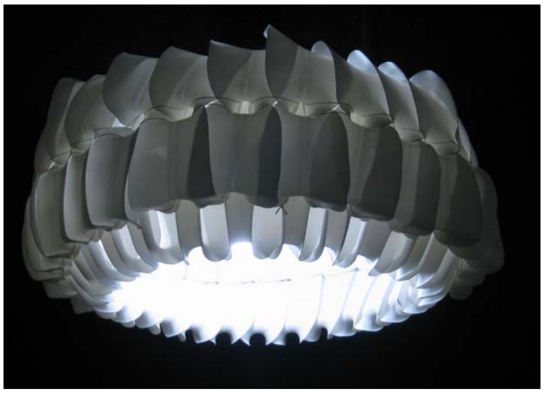

Figure 20. Milkhandle - UFO by Heath Nash
Figure 21. Recycled Water Bottle Art by Michelle Brand

Similarly, Michelle Brand, an artist in the UK, recycled water bottles into a series of artistic and functional interior products. Brand trims the bases of water bottles and connects them with strings to create partitions, lighting fixtures (see Fig. 21), window curtains, and so on.[63] The bottle bases provide a low-key glow in daylight or artificial light. The different light temperatures present various effects through the day. This is another example of the creative utilization of existing waste. The connections between the bottle bases are simpler than the UFO lamp, and the space around each piece enhances the integration between the lamps and their surroundings.

[63] Michelle Brand, "Michelle Brand," Michelle Brand Environmental Design, http://www.michellebrand.co.uk/ (accessed April 5, 2011).

2.3 Mechanical Recycling

Mechanical recycling involves cutting, melting, shredding, contamination separating, floating, extruding, and pelletizing without chemical breakdown.[64] After the wastes are collected, they are chopped into pieces and cleaned to remove contaminants before being sent to manufacturers for new products.[65] Plastic must be sorted carefully to ensure homogeneity.[66] This recycling method is carried out through machines that finish a series of steps, so it requires limited labor and professional techniques during the process. However, it involves a higher level of energy consumption compared to minimal recycling.

For example, Shigeru Ban from Japan did not invent the constructional use of paper tubes; however, he is the first one to carry it forward. Trees are the shared raw material between paper and timber. This connection inspired Ban to use paper like timber in a building. Years later, MINIWIZ from Taiwan pushed forward the idea of "up-cycling," which drove them to develop PET building bricks recycled from post-consumer water bottles.

2.3.1 Case Study I: Paper Tubes - Japan Pavilion, Hannover, Germany, 2000

As a pioneer of alternative material in legal architectural use, Shigeru Ban has come a long way, cooperating with influential architects, consultants, contractors, and other parties who support his ideas with their professional knowledge. However, the most important factor of his success is his capability to incorporate a futuristic vision and traditional values. First of all, he sets his mind free and taps into his imagination. Second, he experiments with ideas and proves their practicality.

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[64] "Plastics recycling," SubsTech, http://www.substech.com/dokuwiki/doku.php?id=plastics_recycling (accessed December 5, 2010).
[65] American Chemistry Council, "Life Cycle of a Plastic Product," American Chemistry, http://www.americanchemistry.com/s_plastics/doc.asp?cid=1571&did=5972 (accessed December 5, 2010).
[66] Meg Calkins, 374.

Finally, he insists on an innovative but viable outcome and protects it from external forces. Therefore, he is not only an architect, but also a warrior who fights for the creative role of architects.

The paper tube structure did not emerge without reason. Ban studied cardboard and paper in college. Recognizing the strength and constructability of these materials, Ban believes that cheap materials like paper can replace more expensive ones like wood and thereby enhance forest preservation through the use of recycled paper. The displays for Alvar Aalto's exhibition in 1986 was the first time paper tubes were used in real projects.[67] For this project, Ban utilized the cardboard core of Aalto's fabric bolts to build a shelf. The cardboard core is used as a hanger that holds the fabric and has no structural purpose, but Ban saw their potential from an architectural perspective. Normally used in tissue rolls, printing paper rolls, fabric rolls, etc., cardboard is treated as a secondary material whose appearance is not emphasized in a product. However, it cost-efficiency, stiffness, flexibility in terms of size, and other advantages drove him to study its possible building applications, regardless of its weakness in protection from weather. Later, he developed paper tubes with modified thicknesses, diameters, and lengths, and had them manufactured for refugee shelters in Nagoya. The Paper Arbour, which he built in 1989, is the quintessence of his accumulated knowledge of paper construction.[68]

Although Ban had been investigating new applications of paper tubes, the Japan Pavilion at the Hannover Expo was a breakthrough in paper design. Cooperating with proof engineer Buro Happold, Ban and Frei Otto created the dynamics between new materials and unconventional building methods, between structure and building form, and between conjunctional flexibility and structural

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[67] University of Cincinnati, "Shigeru Ban Curtain Wall House," College of Design, Architecture, Art, and Planning, www.daapspace.daap.uc.edu/~larsongr/Larsonline/Passive_Solar_files/Ban.pdf (accessed December 2, 2010).

[68] Shigeru Ban and S. Sabine, *Shigeru Ban Architects: Paper Tube Architecture 10: works 1990 - 2000; international positions in architecture; [Ausstellung "Paper Tube Architecture - 10", Hamburg, September 2000, Galerie Renate Kammer]*, Hamburg: Junius, 2000.

rigidity. The biggest success of this project was the interaction between the materials and construction.

❖ Material

The paper tubes in this project were modified to satisfy various requirements. They were manufactured with a diameter of twelve centimeters and a thickness of twenty-two millimeters.[69] The lengths of the tubes varied to enable the diagonal arches of a tunnel thirty-five meters in width and sixteen meters in height. The paper tubes were tested back and forth to balance the profile sizes and their strength. While the tubes in Ban's earlier projects, like the Paper Dome, were unable to curve, the tubes in this project were designed to curve along the gigantic arches.[70]

Ban solved the issue of water resistance with paraffin in earlier projects, but achieved the B2 fire resistance required by the Hannover government for this project without coating.[71] The glue compound mixed in the tubes provided hardness.[72] These additives, unlike some wood additives, allowed the paper tubes to be recycled without harming the environment. Meanwhile, Ban insisted on maintaining the natural appearance of the paper to promote the beauty of modesty. The innovation and ambition of the bare material speaks for itself.

From furniture to columns, walls, ceilings, bridges, and long-span framing, the paper tube has been widely applied in the architectural field. Its clean, simple, and natural appearance creates a modest but strong character. Special joints are required to assemble the cylindrical pieces, but the on-site construction is rapid and simple because of all the prefabricated pieces designed in repetitive modules. The building can also be taken apart and reused easily.

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[69] Shigeru Ban and S. Sabine, 2000.
[70] Riichi Miyake, *Shigeru Ban: Paper in Architecture,* New York: Rizzoli International Publications, Inc., 2009.
[71] Shigeru Ban and S. Sabine, 2000.
[72] Riichi Miyake, 2009.

❖ Constructional Methods

Another unique element of the building was its constructional method—an upswelling process. The paper tubes were first placed in two layers on the platform supported by scaffolds, with one layer facing one direction and the other oriented perpendicularly. One-thousand jacks were distributed underneath to deform the tubes naturally and to gradually form a three-dimensional wavy shape.[73] This process is achieved by two primary elements: flexible arches and joinery.

Ban took advantage of the virtually unlimited length and the pliability of the paper tubes based on his knowledge and experiments with this material. To emphasize the on-site installation and low-tech process, the tubes were bent during construction instead of in prefabrication. Time efficiency, material consistency, and technological viability required simultaneous progress for all of the tubes. However, each curve was designed to curve in specific degrees to create the three-dimensional wavy form (see Fig. 22), which was designed for the lateral strength. Skipping the calculation and pre-manufacturing processes reduced overall construction time. Moreover, the on-site expansion ensured the accuracy of the angles and height of each piece.

Figure 22. Manufactured long tubes

Figure 23. Fabric ties connecting the tubes[74]

[73] Riichi Miyake, 2009.
[74] Riichi Miyake, 2009.

Although Ban had designed and built several paper tube structures by that time, he realized that the dependence on manufactured joints was not cost or time efficient. He decided to bring the evolution to a new level: a grid shell with no joints. Instead of manufactured joints, the tubes were intersected and tied with fabric tapes (see Fig. 23). The flexible interaction between the two layers of tubes allowed the joinery points to change with periodic deformation until the final form.[75]

The Japan Pavilion was designed to be a recyclable tunnel arch.[76] The tunnel had neither interior structural elements nor finishes, so the shell performed as both structural elements and interior finish. This building form required neat and uniform elements with as few additions as possible. Ban's project sustained the principle of recyclability, but the initial origin of the recycled paper tubes was compromised to fulfill the building's practical needs. The success was in the magical contract between the magnificent space and the modest materials.

The flexible connections among the tubes allowed the arches to be pushed up during the construction process. This revealed the importance of the joints in determining the construction and disassembly processes. In the design portion of the thesis, a flexible connecting method that allows the product to be assembled in different ways is considered. Flexible joints are the key to using the same elements to build different forms and allowing repetitive modules to provide multiple functions.

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[75] Shigeru Ban and S. Sabine, 2000.

[76] "SBA_EXPO Japan Pavillion," Shigeru Ban Architects, http://www.shigerubanarchitects.com/SBA_WORKS/SBA_PAPER/SBA_PAPER_10/SBA_paper_10.html (accessed December 2, 2010).

2.3.2 Case Study: POLLI-Brick—EcoARK, Taipei, Taiwan, 2010

The MINIWIZ Company pursues innovative and environmentally conscious design and products. The company has a vision of creative utilization of recycled wastes. For example, the building material of EcoARK is considered a miracle by many professionals inside and outside the architectural profession. The EcoARK appeared at the Taipei International Flora Expo in 2010, and one of its goals was to raise environmental awareness. MINIWIZ built the exterior façade with 1.5 million locally recycled PET bottles, which were called Polli-Brick.[77]

The MINIWIZ design team created the Polli-Brick with the assistance of their engineers and manufacturer through repetitive calculation, revision, and testing. Initially, their architectural degrees and licenses did not provide them with sufficient knowledge to deal with the polymers. The idea of using bottles as a curtain wall system drove them to study various disciplines. Through exhaustive research, they obtained a comprehensive range of knowledge that allowed them to make wise decisions during the revision period. “When many other young people are playing, drinking and having fun, we are actually sitting at the desk and ravenously sucking in all the information,” said Arthur, when recalling the development process of Polli-Bricks.

[77] "EcoARK built with 1.5 million plastic bottles," China Post Online, April 13, 2010, http://www.chinapost.com.tw/taiwan/local/taipei/2010/04/13/252317/EcoARK-built.htm (accessed December 6, 2010).

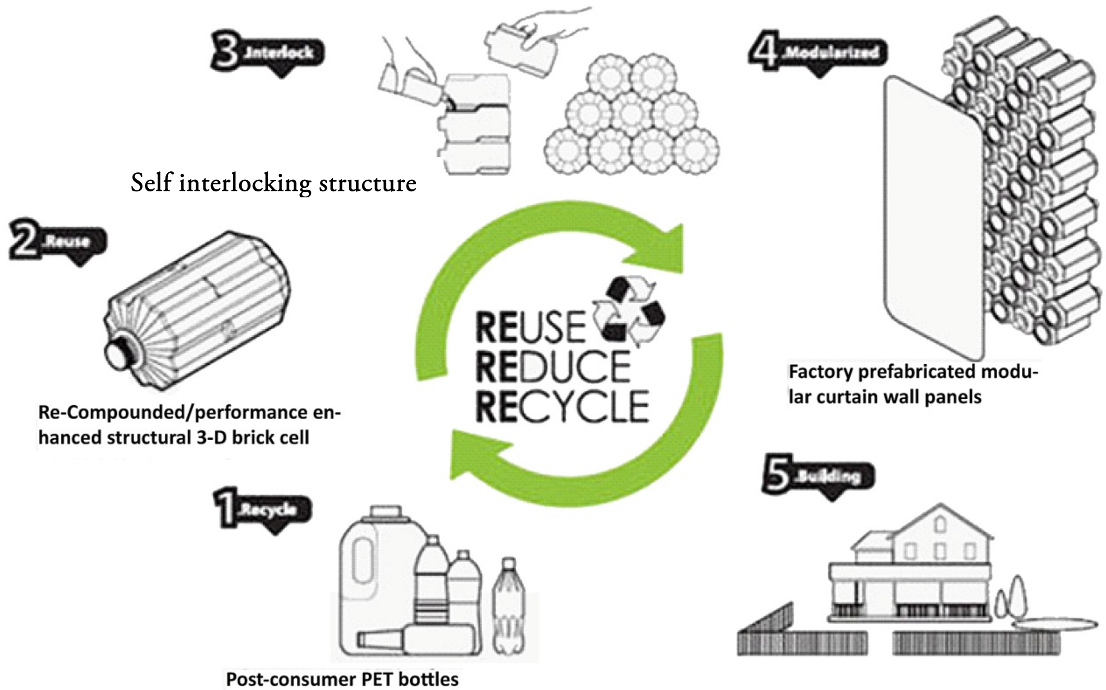

Figure 24. The lifecycle of Polli-Bricks[78]

While the company enforces the idea of up-cycling, lifecycle sustainability is also an important target. MINIWIZ has a more comprehensive definition of sustainability compared to many other green products. The image below shows the lifecycle of PETE plastic bottles once recycled for Polli-Bricks. From its recycling, production, application, performance, end of its life, and back to recycling, the product is constantly concerned about environmental impacts and efficiencies.

- **Bottle Production**

There are many recycled PET bottles on the market, but what makes Polli-Bricks special is the "up-grade recycling process" versus the more common downgrade recycling. While many plastic bottles are recycled into packaging materials, fabrics, carpet, and so on, MINIWIZ recycles them into a building façade material with a much higher value in function and cost.

[78] Engineering.com, Inc., 2010.

This idea is an efficient solution to many environmental problems related to the construction industry: resource shortages, energy consumption, CO_2 emissions, and waste disposal.

The raw materials of Polli-Bricks can be recycled bottles or baled PET units. Moreover, energy conservation is addressed in the production process of the bricks, which are made from plastic flakes instead of pellets. Typical mechanical recycling shreds the wastes into flakes and makes them into pellets before they are made into new products, but the Polli-Brick has skipped this step. Therefore, it is more energy-conserving and time-efficient.[79]

Unlike many other methods of PET bottle recycling, the Polli-Brick is formed through mechanical recycling. This recycling method retains the translucency of the PET bottles, and allows light to transmit between the exterior and interior (see Figure 25). The product is transformed so that it has a higher stiffness and a uniform shape to provide constructible functionality. The hexagonal profile geometrically provides strength to the bottle section, allowing stable vertical collaboration and negating the need for additional materials to fill the gaps (see Fig. 26).

Figure 25 Polli-Brick light transmittance

Figure 26. Polli-Brick

[79] Engineering.com, Inc., 2010.

Also, in order to provide material stabilization under UV exposure, three levels of UV coating are applied to the material. According to Mr. Arthur Huang, the founder of MINIWIZ, the UV additive is added during the bonding process. A second layer is added to the bricks before they cool down and a third layer is added in the form of films. The UV-proof PET bricks are thus long-lasting and stable; they do not degrade or release harmful emissions.[80] At the same time, the UV-resistant agent as well as other chemical additives is measured so that the recyclability of the bottles is not affected.

Meanwhile, the design of the recycled bricks retains the bottle form so that the air inside performs the function of insulation.[81] It is similar to the air cushion of the Biodome in London, which utilizes the air between the plastic bubbles for a thermal barrier. This design not only reduces the cost, energy, and resources required for a physical insulation layer, but also emphasizes the idea of pursuing maximum outcomes from minimal materials.

❖ Bottle Form

Regarding the utilization of minimal material, the Polli-Bricks also presented the conservation and homogeneity of materials in the form of the bricks. The challenge lies in how to minimize the need for additional elements to provide the wall function.

Many are curious and suspicious about the "efficiency of structural capability" that Polli-Brick is claimed to have. The trick of the self-supporting character is the hexagonal structure inspired by a honeycomb. The hexagon allows the bricks to transfer the vertical loads onto the bottles below straight down or at an angle, which avoids the greater pressure of a perpendicular angle. Also, the pressure is transferred from one corner to another, and it

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[80] Engineering.com, Inc., "Polli-Brick Interview," GREEN 3D HOME, December 6, 2010, http://www.green3dhome.com/Community/Articles/PolliBrickInterviewPart1.aspx (accessed December 6, 2010).
[81] Engineering.com, Inc., 2010.

reduces the direct impacts on the sides. Therefore, the issue of load-bearing qualities becomes a matter of bottle size and thickness as well as the chemical contents of the material, which, of course, is a complicated process of back-and-forth discussion and modification.

Meanwhile, the lateral load resistance of the wall is also an issue. The bottles are manufactured to be smooth and shiny, under the aid of chemicals, but the smoothness makes it almost impossible to lock the bottles in place with friction. Another solution—adhesive—is also not practical in terms of the reuse and recycling processes in the lifecycle of the bottles. Therefore, the brick-to-brick, panel-to-panel, and panel-to-other connections are highly dependent on mechanic systems within the bottles.

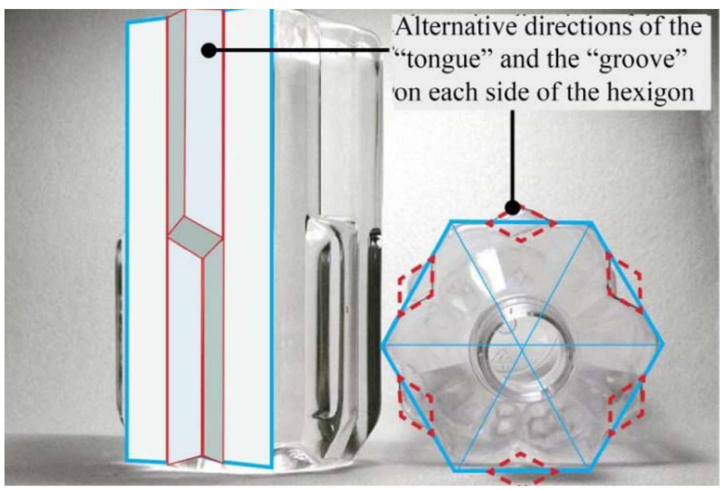

Figure 27. Polli-Bricks tongue and groove system

In terms of the brick-to-brick connection, the problem is solved by the bottle form inspired by the tongue and groove connection of ancient Chinese architecture. The company has chosen the solution that minimizes alterations to the hexagonal form. Figure 27 shows the interlocking stops on each side of the hexagon. Each side of the hexagon is divided into three vertical sections; the middle section has the tongue and the groove on either top or bottom, which alternates on every other side. When three bricks are put together to form a triangle, the bottles are locked with each other longitudinally.

The stability of the bottles can resists natural disasters like earthquakes and storms.[82] This design is also derived from the desire to construct a wall without additional sealant between the bottles. As a result, the whole wall can be directly recycled, avoiding the tedious steps of sorting and separation.

However, this secure installation also leads to difficulties in replacing the product without impacting other parts of the building. The bottles and panel modules can only be removed one by one from the outside in. Removal requires at least two sides around the rectangular panel to be empty, since the hexagon shapes of the bottles form a zigzag pattern, which prevents the panels from being moved parallel to one another. Therefore, the panel has to be removed from an angle, and it conflicts with the horizontal or vertical tracks. This issue remains a problem to be solved in future versions of Polli-Bricks.

❖ **Wall Connection**

Besides the bottle form, another brilliant design is the bottle neck that provides practical functions. The bottle neck is the key component in the unity of the entire wall. It connects the bottle panel with external plastic sheets, steel plates, and other components of the wall system.

According to Jarvis, the thickness of the bottle neck is carefully engineered to support a heavy weight. The neck acts like an embedded bolt that locks various external elements between the bottle cap and the bottle. The bottle cap, which is made of HDPE, has higher

[82] "EcoARK built with 1.5 million plastic bottles," China Post Online, April 13, 2010, http://www.chinapost.com.tw/taiwan/local/taipei/2010/04/13/252317/EcoARK-built.htm (accessed December 6, 2010).

mechanic strength than PET, and it performs as a giant bolt cap.[83] Figure 28 shows the connection of steel plates designed for C-channel frames. The mechanic connection with no welding, heating, or adhesive is also a strategy for the ease of disassembly, which allows the wall components to be reinstalled immediately, in order to minimize the energy and resources required to recycle the building materials.

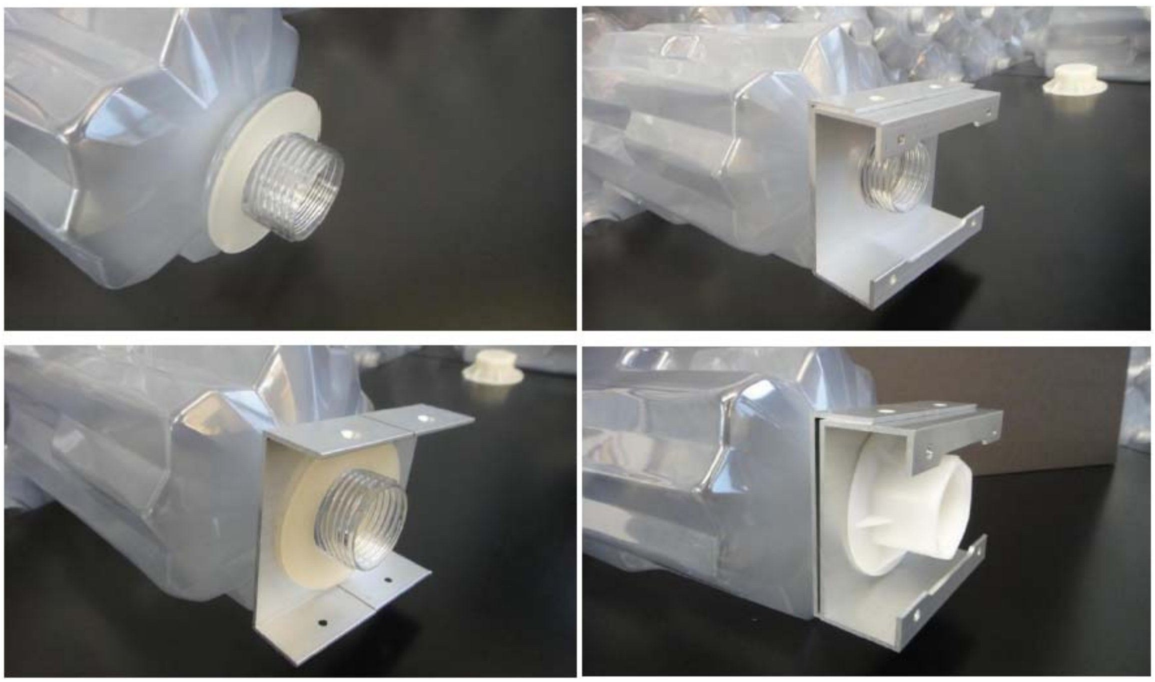

Figure 28. Installation of C-channel steel plates, MINIWIZ, March 16, 2011 (Photo Source: author)

Also, the bottle neck and cap are designed to integrate with other external objects. For instance, the cap is penetrated and secured with a specific light bulb. The light bulb is protected by the hollow bottle body; the bottle wall projects attractive effects according to the lights.

[83] Jarvis Liu, interview by author, In person interview, Taiwan, March 16, 2011.

❖ Plastic Sheet

Unlike a conventional building wall that requires layers of different protective barriers and adhesive, Polli-Brick is designed to minimize the material and achieve maximum function as a unity. The wall is composed mainly of four layers of thin plastics. Theoretically, the hollow bottles create two layers, which are the main protective and structural elements along the wall. These provide weatherproofing, impact resistance, and UV resistance. Meanwhile, two additional external and internal plastic sheets provide extra strength and protection. Depending on the local regulations, the plastic sheets can be PVC or PC, both of which are clear and can be integrated with protective films or additives. The two plastic sheets are the backup element that Polli-Bricks have not fulfilled. The ease of disassembly allows the opportunity to maintain the homogeneity of the materials when they are recycled.

With the plastic sheets, the four vertical layers of the plastic surfaces create three layers of air in between, which provide double insulation in the wall panel (see Fig. 29). The enclosed bottle provides insulation that prevents the heat from rapidly travel to the other side of the wall. In addition, the air circulation between the bottles and the plastic sheet, as shown in the up and down arrows, creates a secondary circle of air movement that keeps the panel module internally cool and dry. The innovative use of air results in high insulation and shows the importance of a holistic relationship between elements.

The unity of the entire wall system was carefully considered in the design of the bricks. Jarvis suggests fastening the two plastic sheets on the bottle necks purely to the bottle caps on either side of the wall panel (see Fig. 30). In order to ensure uniform pressure on each side of the wall, the plastic sheets are secured by the evenly distributed caps. [84]

[84] Jarvis Liu, interview by author, In person interview, Taiwan, March 16, 2011.

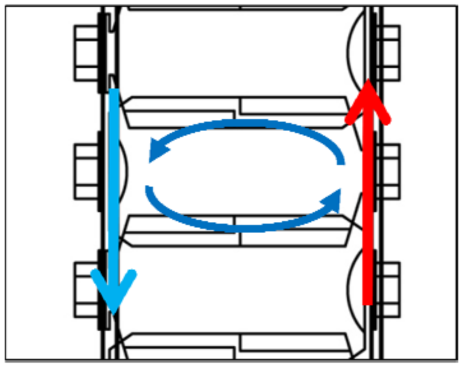

Figure 29. Two types of air insulation in a Polli-Brick panel

Figure 30. Top plastic sheet fastened on the bottle panel, MINIWIZ, March 2, 2011(Photo Source: author)

These clear plastic sheets are used mainly to secure the placement of each bottle and to enhance wall performance with proper chemical additives; however, it does nothing in carrying the vertical or lateral loads of the wall. Another important function of the sheets is modularizing the bottles for ease of pre-manufacturing and transportation. In other words, the bottle bricks are strong enough to endure pressure from the other bottles, the roof, and external impacts, like hurricanes. The plastic sheets are installed for the purpose of time-efficiency and protection.

The Polli-Brick is a simple representation of various complex thoughts including interlocking, self supporting, and passive cooling characteristics as elements that can be adopted in later designs. Using the bottle neck as the connecting agent of different wall members is also a smart way to reduce the use of additional materials, which helps to reduce the use of material and simplify the assembly process.

2.3.3 Case Study: Plastic Lumber—Axion International, USA, 2010

Plastic lumber is an increasingly popular recycled plastic product used in the construction industry. There is a tendency for the plastic lumber to replace wood in various exterior applications. Although it is known for its weak tensile strength, modified construction details and engineering allow this material to be adopted for heavy duty structural use. For example, the US Army Transportation Corps built one of their railroad bridges (see Fig. 31) using Recycled Structural Composite (RSC) from Axion international Holdings, Inc.[85]

This bridge is approximately 40 feet long, and it is designed to carry military trains up to 120 tons at up to 40 miles per hour. The old bridge was aged and rotted, which drove the department to look for solutions that expanded the longevity of the structure. The bridge is made of RSC from piles, pile caps, I-beams, trusses, and railroad ties among other things. The engineers and Axion International worked closely to resolve challenges by altering the material compounds, dimensions, and placements. This was just the beginning of the extensive use of plastic lumber in heavy duty structures. According to Tom Nosker from Rutgers' Advanced Polymer Center, the next bridge is expected to span up to 500 feet.[86]

In addition to the environmental benefits, cost efficiency was also a reason to challenge the structural design of the bridge. A bridge built with pre-assembled RSC (see Fig 32) is 10% cheaper than one

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[85] Joseph Blumberg, "Axion Installs First Ever Recycled Plastic Rail Road Bridge at Fort Eustis, Virginia," Office of Technology Commercialization, May 10, 2010, http://otc.rutgers.edu/about/latest-news.php#s06 (accessed August 22, 2011).

[86] Carl Blesch, "Plastic Lumber Flexes its Muscle in Army Railroad Bridges," Rutgers FOCUS, June 2010, http://news.rutgers.edu/focus/issue.2010-06-03.4448585852/article.2010-06-03.9148284220 (accessed August 29, 2011).

built with treated wood.[87] Although plastic lumber in standard sizes is currently more expensive than conventional wood, the feasibility is expected to increase in the future with improved technology. Although custom-made products are more expensive than standard sizes, the mass manufacturing of the product will potentially reduce the cost.


Figure 31. Axion composite railroad (Fort Eustis, Virginia)   Figure 32. Axion RSC I-Beam

- **Recycled Structural Composite**

RSC is composed of 100% post-consumer HDPE from milk bottles and detergent bottles, as well as PP and PC from automobile bumpers.[88] The different properties of these combined polymers complement each other because they have characters that other polymers lack. This is also one of the main reasons why composite materials become so popular. Not only does it reduce the concentration on one material, but it also provides more useful features for a product.

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[87] Chusid Associates. "10 Best New Building Products - 2009." Building Product Marketing. http://www.buildingproductmarketing.com/2010/01/ten-best-new-building-products-of-2009.html (accessed August 22, 2011).

[88] Recycled plastic used in Fort Eustis bridges." Virginia Business - VA business news. March 29, 2011. http://www.virginiabusiness.com/index.php/news/article/recycled-plastic-used-in-fort-eustis-bridges/ (accessed August 29, 2011).

The stiffness of the material is one-tenth that of concrete and one-hundredth that of steel, [89] so the sizes of the structural members had to allow for the intended capacity of the bridge. The section of the bridge shows its basic structural elements, which are generally similar to steel and concrete construction.

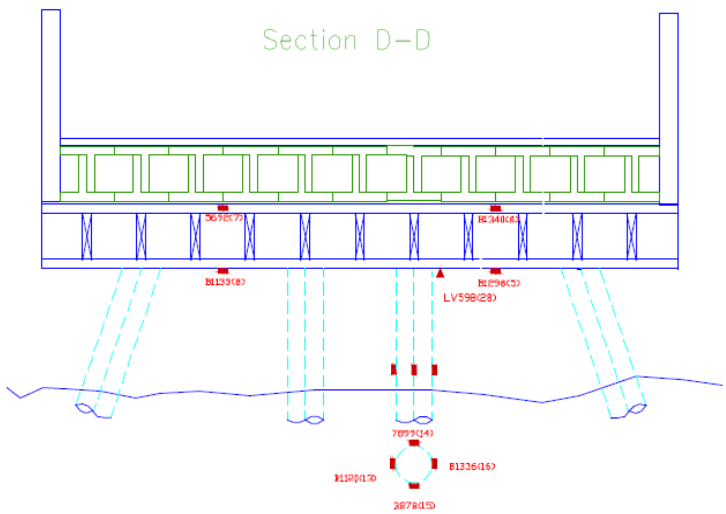

Figure 33 Cross-section of the RPC Bridge showing different types of RSC members[90]

2.3.4 3form 100 Percent Panel

100 Percent is a fully recycled post-consumer HDPE material developed by 3form, Inc (see Fig. 34) that responds to the call for the reduction of our ecological footprint. This product is for interior use, like countertops and desktops, and it has a strong emphasis on aesthetics. Since the 100 Percent is not engineered for structural use, it allows a wide range of forms and dimensions for different uses. HDPE is shredded into small flakes and compressed into solid pieces that are engineered to carry certain loads.

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[89] Axion International. "REPORT US ARMY Corp Engineers ERDC-GSL TR-10-19_Bridge Load." Axion International Recycled Plastic Railroad Ties, I-Beams, Boards, and Marine Pilings. http://www.axionintl.com/library_pilings.html (accessed August 25, 2011).

[90] Axion International, "REPORT US ARMY Corp Engineers ERDC-GSL TR-10-19_Bridge Load," Axion International Recycled Plastic Railroad Ties, I-Beams, Boards, and Marine Pilings http://www.axionintl.com/library_pilings.html (accessed August 25, 2011).

Figure 34. 3form 100 Percent® Desk[91]

This product is a representative of production through shredding and compressing. The panels are strong enough for various interior applications. The panel achieves type CC2 in flammability testing, and is thus qualified for general purpose. Also, it is certified for indoor air quality, which proves that recycled HDPE has the potential for safe indoor usage.

According to 3form Inc., each panel recycles a thousand containers. Moreover, the firm has established a reclamation system to handle used or damaged products. This closed-circle process minimizes the plastic that goes to landfills in two ways.92 Besides conserving wood or other conventional materials, the product can be used to create various kinds of panels for different uses and appearances. It not only gives the material a lively appearance, but also reminds users of the art of recycling.

[91] "100 % Recycled Architectural Resin Panels," 3form, http://www.3-form.com/materials-100_percent.php (accessed December 6, 2010).
[92] Ibid.

2.4 Feedstock Recycling

Chemical recycling breaks down the polymers into monomers in order to recombine and create new polymers. This process allows mixed plastics, so the process requires less sorting efforts. However, it has higher threats to the environment and human health.93 Typical recycling creates gases like CO and H2 and byproducts like chlorides. Such recycling methods include gasification, pyrolysis, cracking, conversion, and incineration, among others.94

Most feedstock recycling requires the use of natural gas and petroleum, which make up 10% of fossil fuel consumption. Besides, the process sometimes creates toxic byproducts that may become pollution if not handled properly.

Conclusion

There is no best way to reuse or recycle materials. Recycling and application methods may vary based on available resources and technology. From simple reuse to professional modification, recyclables can be flexibly applied to suit different needs and expected effects. However, it is important to utilize the advantages of the material to promote innovative design and to recognize the limitations of the material to adjust constructional methods for higher efficiency. The examples above show an emerging industry that recycles wastes into constructional materials. With a proper design and installation method, the recycled materials have the potentials to be integrated with everyday living in a variety of applications. Gradually, the products will improve from expensive and single-purposed to cost-effective, energy-efficient, durable, and multifunctional.

[93] Meg Calkins, 390.
[94] Summary of "Plastics Waste - Feedstock Recycling, Chemical Recycling and Incineration," ChemTec Publishing, http://www.chemtec.org/proddetail.php?prod=978-1-85957-331-0 (accessed December 6, 2010).

Chapter 3 High Density Polyethylene (HDPE)

HDPE is a material frequently used in bottles for liquids like milk, laundry detergent, and lotion. Out of the major packaging plastics, PETE, PP, and HDPE are more suitable for constructional use. However, while PETE and PP are used half as much as HDPE, HDPE has a lower recycling rate than the other two.[95] Therefore, there is a greater need for HDPE recycling. The studies of the HDPE characteristics provide an important information base for the new designs of the potential recycled products.

[95] Meg Calkins, 383.

3.1 The Trend of Alternative Materials

Conventional materials like stone, wood, concrete, and bricks are still commonly used. These materials currently have higher efficiency in application and higher effectiveness because of long-existing safety requirements, legislative guidelines, and building construction methods that are designed for them. Meanwhile, conventional materials are also more cost-efficient because of their established system of manufacturing, transportation, sale, and post-consumer handling.

However, the emergence of alternative materials is becoming more and more popular due to technological developments. The unconventional materials, like HDPE, obtain some qualities that are equivalent to those of conventional ones. In addition, because the alternative materials have new properties, they often bring exciting and unexpected advantages to a product. Although the manufacturing of products made of alternative materials costs more, requires custom-made accessories, and faces more safety restrictions, the issues will lessen when the product proves its viability and is mass manufactured. Each new product or new material, like HDPE, faces the same barriers, and the first step to bringing the product to life is convincing people of its values.

Compared to several existing building materials, HDPE proves a certain amount of capability that is compatible with conventional materials. Also, HDPE introduces some new features which can possibly be used in construction.

3.2 Introduction to HDPE

When plastics are promoted as building materials, limited knowledge of the risks and disadvantages of using them may keep people from truly considering them. Is it reliable? Will it release toxic emissions? Is it strong? However, conventional materials also have issues that people choose to accept in order to compromise on desired qualities.

3.2.1 What is HDPE?

HDPE stands for high density polyethylene, which is in relevant to other PE products like medium density polyethylene (MDPE) and low density polyethylene (LDPE). HDPE is extracted from petroleum through high heat. HDPE has a density of 0.94g/cm^3, slightly lighter than water.[96] Its density is higher than the other two types of PE because of its neat arrangement of the single-chain of its chemical structure; LDPE has irregular branches along it. HDPE is Type 2 in the Resin Identification Codes, which create a guideline for people to process recycling. It is also one of the biggest contributors to everyday plastic use.

HDPE and LDPE are known for their ease of forming, cost efficiency, and tenacity. HDPE is the plastic with the highest softening temperature; it is normally used in sewer pipes, storm water structures, bottles, grocery bags, recycling bins, playground equipment, plastic lumber, etc. LDPE has high flexibility and transparency, so it is commonly found in plastic bags, 6-pack rings, dispensing bottles, and wash bottles.[97]

Although HDPE has higher thermal resistance and strength than LDPE, they are both highly recyclable materials. However, the recycling rate of plastic in MSW was only 5.7% in 2005. Of the

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[96] "Data Table For Polymers: Commodity Polymers: HDPE." MATBASE. http://www.matbase.com/material/polymers/commodity/hdpe/properties (accessed August 25, 2011).
[97] "Plastic Revolution: Plastics, De-coded," Plastic Revolution, http://plasticrevolution.blogspot.com/2008/09/plastics-de-coded.html (accessed October 6, 2010).

remaining 27,000 tons, 11,600 tons of HDPE and LDPE could have been recovered and used for other purposes.[98] These plastics can be fully recycled back into their original forms or into landscaping products, bottles, plastic bags, decking, fencing, and structural elements like plastic lumber. Considering its extremely low resource consumption, embodied energy, and carbon footprint, plastic is one of the most ideal materials that can be used to reduce greenhouse effect. Also, when plastic takes centuries to degrade, the best waste management method for it is recycling. However, plastics raise another type of environmental issue.

3.2.2 Properties of HDPE

HDPE, like many other types of polymers, is highly durable under proper conditions. The balance between the longevity and functional properties of HDPE makes it a viable material for a wider range of building use. According to the accumulative information obtained from the Material Properties Database website, HDPE has certain advantages over wood and other types of plastic materials:[99]

- Low Water Absorption
- High Chemical Resistance
- High Impact Strength
- Variety of Color

One of the biggest concerns regarding plastics in building application is that they can be melted by fire at certain temperatures and release a dense toxic smoke and combustible vapor that enhances the fire. Moreover, plastic is, after all, less structural than metal, concrete, wood, and other conventional materials because it deflects, expands, and deforms under temperature change, heavy loads, and other factors.[100] These issues need to be solved before it makes further steps in the construction field.

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[98] Meg Calkins, 382.
[99] See Appendix A
[100] Victoria Ballard Bell and Patrick Rand, *Materials for Architectural Design* (London: Laurence King Publishing, 2006) 220.

3.2.3 HDPE vs. Wood

Wood has been a major construction material for thousands of years. It is a handy material that offers durability, flexibility, aesthetics, and sustainability. While other materials such as metal and concrete have emerged, none of them have succeeded in replacing wood's position in the constructional industry. The low energy consumption is one of the most important factors that keep lumber manufacturers alive, in addition to wood being a cheap available resource.

- **High Water Resistance**

There is also a tendency for HDPE to replace wood because of the longevity of the material. HDPE is known for its water absorption rate as low as 0.01%. Not only is it much more moisture-proof than wood, its water absorption is also about one-fourth that of PVC and one-seventh that of polycarbonate (PC).[101] The water resistance of HDPE makes it the most suitable material when dealing with moisture and trying to protect other building elements from rotting or being polluted.

HDPE is recommended to replace wood in applications of decking, railing, fences, landscaping timbers, cladding, siding, opening frames, railroad ties, and chairs. For example, unlike conventional wood decking, plastic does not have the problems of rotting and cracking due to weather factors nor will it encounter termite problems. While wood lasts only about seven years, plastic lumber lasts fifty years or more.

[101] See Appendix A

❖ **High Value for Reasonable Price**

Although the price for HDPE lumber is generally two to three times higher than regular wood, the lifecycle cost is greatly reduced by its durability. The maintenance and reconstruction fees that it avoids highly increase the cost-efficiency of the building life.

Also, the price of wood is expected to grow higher and higher in the future while recycled plastic lumber will cost less with mass production and technology development. From a long-term perspective, the plastic products will become increasingly feasible.

❖ **Reduction of Ecological Footprint**

In spite of the low energy required to process wood products, there are two major environmental issues emerging from wooden construction nowadays. Deforestation is a global ecological problem caused by the high demand for lumber and wood fiber. Such deforestation makes these places vulnerable to natural disasters.

In contrast, plastic lumber contributes to reducing our ecological footprint. According to the American Chemistry Council, each plastic railroad tie consumes 200 pounds of plastic, which is equivalent to 1,200 bottles.[102] Not only does this product reduce MSW plastic and consumption of conventional hardwood, it also dramatically reduces the embodied energy of the railroad ties.

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[102] The American Chemistry Council, "Plastics Division: recycled plastic lumber" The American Chemistry Council http://www.americanchemistry.com/s_plastics/doc.asp?SID=6&DID=5987&CID=1582&VID=178&RTID=0&CIDQS=&Taxonomy=False&specialSearch=False (accessed October 7, 2010).

❖ Reduction of Chemical Pollution

Another major environmental issue with wood materials is the chemical treatments used to preserve wood, which can harm the environment and building users. Wood that has undergone pressure treatment is one of the typical hazardous wastes from a construction site. The handling of these woods is almost as tricky as that of plastic. The treatment may involve inorganic penta, creosote, and arsenate, like chromated copper arsenate (CCA), and ammoniacal copper zinc arsenate (ACZA). These chemicals will not biodegrade, so they will remain in the earth and change the quality of the soil, which may result in the instability of the building foundation. Therefore, the disposal location of treated woods is strictly regulated. Also, the treated wood releases toxic gas while burning as well as harmful ash that should be disposed of carefully and is not accepted by landfills.[103]

While the disposal of plastic has less relevant regulations, treated wood and plastic have similar environmental issues. Wood degrades and deposits toxins into the soil, which are difficult to spot and quantify. It requires professional detection to ensure the safety of the soil before it can be used for another purpose. Unlike treated wood, the plastic remains in its physical form. The solid and visible plastic waste is thus relatively easier to clean up. Hence, considering that they both bring environmental problems, it is more convenient to handle the plastic waste than the chemicals from treated wood.

❖ Mouldability

The options of extrusion, injection, and blow molding make it technically possible to mold HDPE into any form. A modular design that adopts only one type of molding minimizes

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[103] Environmental Management Division Office of Solid Waste Management, "Fact Sheet Pressure-Treated Wood Management," Hawai'i State Department of Health, July, 2000, hawaii.gov/health/environmental/waste/sw/pdf/trtdwood.pdf (accessed November 18, 2010).

the process of formation. Inspired by the Polli-Bricks by MINIWIZ, the modular unit in this project is designed to provide certain structural capability and locking mechanics.

Also, although the HDPE in this project will not be recycled into another bottle, it will be designed as a modular unit that provides multiple functions in a simple form. Since the unit can be molded into technically any form, there is a great potential for the design to integrate functionality with efficiency. The form of the units can also enhance their efficiency by allowing them to lock together, stack on each other, and adapt to the existing framework.

❖ **Weak Mechanical Strength**

Despite the many advantages of recycled HDPE products, there are challenges for a designer applying this material in building use, especially in terms of safety and health issues. These weaknesses can be easily solved by adding respective agents, but it is preferred to minimize the additives in the material to maintain a high level of homogeneity.

Recycled HDPE lumber is not used for structural beams because it has weak tensile and compressive strength. There are several categories of wood based on their strength. Class I and Class II wood have about one-sixth the strength of HDPE, while Class III and IV wood have a much wider range of strength. Class II and IV have a tensile strength up to 163 MPa, five times higher than that of HDPE. Efforts have been made to resolve this problem, one of which is adding a tensile strength agent commonly known as talc.[104]

Meanwhile, the compressive strength of the HDPE is about half that the wood, which means that it is structurally weaker.

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[104] Todd Reed, Interview by author, Phone interview, Honolulu, August 23, 2011.

❖ **Low Fire-Resistance**

According to data accumulated by Machinist-Materials, Inc., the melting point of pure HDPE is 130°F.[105] However, a majority of commercial HDPE products have a melting temperature over 220 °F.[106] In contrast, wood has a much higher combustible temperature because of the moisture inside. Although the wood fibers can be burnt at 220°F, it takes a period of time before the water is evaporated to reach 450°F.

The homogeneity of HDPE, which is ideal for recycling, is a disadvantage in its fire-proofing, because of the lack of assistance in postponing ignition.

❖ **Compromised Transmittance**

PE is generally transparent in its thin film or pellet form, before additives are added to it. However, when its thickness increases, its transparency reduces due to the crystallinity in the material. Moreover, additives like the UV agent come with color. Although it is only 3% in a 500-pound portion of plastic, the translucency is compromised for functionality.

3.2.4 HDPE vs. PVC

Polyvinyl chloride (PVC) is the most commonly used plastic in construction; it is often found in pipes, the exterior finish, the roof membrane, flooring, windows, bathroom curtains, and inflatable products. Although PVC is currently the most popular plastic type in the building and construction sector, other materials share the market. For example, PVC is required for plastic building applications in Taiwan because of its outstanding fire resistance. Contrarily, the use of PVC is

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[105] See Appendix B

[106] Indian Oil Corporation Ltd., "MATERIAL SAFETY DATA SHEET HDP," Indian Oil, www.iocl.com/Products/MSDS-HDPEJan09.pdf (accessed September 6, 2011).

discouraged in Germany because of its carcinogenic effects on workers. In the US, HDPE pipes are suggested to replace PVC pipes in order to reduce environmental issues.

The most concerning disadvantage of PVC is its toxic component. This resin accounts for the least embodied energy of thermoplastics because it is composed of more than 50% chloride. While the large supply of brine and the amount of energy required to extract PVC reduces its embodied energy, its shorter longevity actually increases the energy costs of its recycling life. Moreover, PVC produces severe environmental and heal threats during its production.[107] Dioxin, ethylene dichloride, and chlorine gas are harmful and carcinogen chemicals; the latter two are on the Environmental Protection Agency (EPA)'s hazardous list. Therefore, the use of PVC has been discouraged.

Another factor in the decision to replace PVC with HDPE as a pipeline material is its high chemical resistance. Although PP has the same water absorption rate as HDPE, it does not have the same chemical-proof character. HDPE can endure various types of organic solvents. The Chemicals Resistance Table listed about 300 types of chemicals, and HDPE reaches a "satisfactory" level for more than 80% of them.[108]

As discussed earlier, PVC contributed to 75% of the plastics used in the construction industry, which made up 19% of the overall plastic. The harmful byproducts of PVC are catching people's attention.[109] However, HDPE and LDPE, which are ideal alternatives to PVC, also produce pollution, in spite of the relatively stricter regulations for their recycling.

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[107] Meg Calkins, 379.

[108] Chemicals Resistance Table Low Density and High Density Polyethylene. Borealis. www.borealisgroup.com/pdf/chemical-resistance/chemical-resistance-hdpe-ld.pdf (accessed August 23, 2011).

[109] Meg Calkins, 374.

3.2.5HDPE vs. Polycarbonate (PC)

PC is often a replacement for glass because of its transparency. It has a similar appearance to glass but a much lower density. Therefore, it is often used to reduce the weight of a product. It is made in the form of a solid piece or a hollow panel. Depending on the requirements, PC can be used both indoor and outdoor.

The most common type of polycarbonate that we see is polycarbonate of bisphenol A (PBA), which is a thermoplastic. It can be found in lightweight eyeglasses, compact discs, shatterproof glass, cell phones, computers, and household appliances.[110] Polycarbonate can endure heat up to 150ºC.[111] It is safe to transport and store; and its toxic-free character makes it an ideal material for all kinds of food-related packaging, under monitor of the US Food and Drug Administration (FDA).[112] For its considerable advantages, polycarbonate is normally twice as expensive as HDPE. According to a summary by the American Chemistry Council, there is currently no proof of health threats from exposure to BPA, which is the raw material of polycarbonate. Under normal conditions, possible human exposure is only 1/400 of the maximum acceptable amount for a human body.[113]

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[110] American Chemistry Council, "Bisphenol A: Information Sheet Environmental Safety: An Overview," under "BPA (Bisphenol A) Fact Sheets," Bisphenol A (BPA) Information & Resources, http://www.bisphenol-a.org/about/infosheets.html (accessed October 7, 2010).

[111] The Department of Polymer Science, the University of Southern Mississippi, "Polycarbonates." Polymer Science Learning Center, http://pslc.ws/macrog/pc.htm (accessed October 7, 2010).

[112] spi: the plastics industry trade association, "The Safety of Polycarbonate Packaging," SPI - Society of the Plastics Industry, http://www.plasticsindustry.org/AboutPlastics/content.cfm?ItemNumber=716&navItemNumber=1126 (accessed October 7, 2010)

[113] American Chemistry Council, "Bisphenol A: Information Sheet Human Safety: An Overview," under "BPA (Bisphenol A) Fact Sheets," Bisphenol A (BPA) Information & Resources, http://www.bisphenol-a.org/about/infosheets.html (accessed October 7, 2010).

Its thermoplastic character allows polycarbonate to be softened and reformed by change of temperature. The recycling process differs from object to object, but most of them are part of closed-loop recycling, and a few are recomposed into other objects.

During recent years, polycarbonate has been a popular material for exterior cladding and skylights. When natural lighting became one of the essentials in building design, its light transmittance allowed this material to compete with some solid-colored materials and to become part of the building envelope. Polycarbonate is normally made into flat, curved, or corrugated sheets, which while called "structural polycarbonate," is not currently applied as independent structural elements.

3.2.6 HDPE vs. Paper

Generally, the creation of a paper product is a process of reutilizing the fibers, but in some cases, the new composition and new form provide unexpected functions. Paper may be commonly considered flimsy, but is also widely used for protection and supporting purposes. The nature and geometrics of paper allow creative methods to utilize its planar strength.

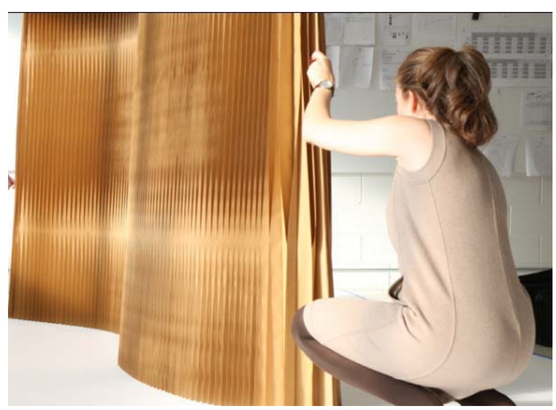

Figure 35. Molo softwall with embedded lights; Figure 36. Molo softwall in cardboard paper[114]

[114] Ibid.

The honeycomb structure has been very popular in the alternative material market recently. Similar to corrugated cardboard, people are fascinated by its structural capability created by repetitive thin pieces that share bonds with each other. The honeycomb structure allows various types of so-called flimsy materials to express their physical properties like transparency, color, texture, and recyclability, in a broader range of applications. For example, Molo Design has created several outstanding products from an altered honeycomb principle (See Fig. 35 & 36).[115]

Plastics can also have a honeycomb structure, which is mostly a rigid piece that is used for a sandwich structure supporting a panel. A plastic honeycomb reduces weight without sacrificing certain strength.

Different from plastic, the honeycomb can be rigid or foldable depending on the material type, and both styles aim to allow the product to be free-standing. For a foldable paper honeycomb fifteen feet in length, the contracted form can be as thin as several inches.[116] With the honeycomb profile on the same plane, the product is horizontally expandable, preferably in a curved shape. However, since the top and bottom are free to move in different angles, though within a limited range, the object can be curved vertically as well, allowing a three-dimensional dynamic experience for users. The dramatic difference in sizes between storage and application conditions provides incredible flexibility in function and spatial use.

The material quality is also flexible for different applications. To provide enough strength when the product is open, a manufacturer may use kraft paper or other stiff materials. For wall applications, it is made of fire-retardant paper to achieve a certain fire-rating.[117] Paper honeycombs are also commonly used in ornaments, lanterns, and other accessories, which require maximum volume out of a minimum weight, regardless strength and rigidity.

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[115] Molo Design, "products softwall + softblock modular system," Molo design, http://www.molodesign.com/products (accessed November 1, 2010).
[116] Source: Image from Molo design.
[117] Blaine Brownell, "Plastic and Paper," In *Transmaterial: A Catalog of Materials that Redefine our Physical Environment.* 1st Ed. New York: Princeton Architectural Press, 1899, 174.

3.3 Constructional Usage of HDPE

Recycled plastic lumber is one of the most commonly known recycled plastics in the building and construction sectors. It has much higher durability than wood lumber, and unlike wood, plastic with a controlled amount of protective additives is still recyclable.

There are two types of 100% recycled plastic lumbers, and both the single-resin and commingled types can be made of up to 100% post-consumer recycled plastic. Single-resin plastic lumber is made of one type of plastic. This character allows the lumber to have consistent properties throughout the entire piece. Also, the single component simplifies the process of recycling. The major materials are HDPE or PVC, but because of the environmental problems that PVC brings, its production has been highly limited.

The commingled plastic lumber is composed of multiple plastics.[118] The various properties of the plastics complement each other, providing a more comprehensive capability. The diversity of resources reduces the cost of the product; however, it also creates complexity for the recycling process. Nevertheless, the variety of components leads to flexibility in product performance. However, plastic lumber has a weaker tensile strength than wood. This becomes one of the biggest constraints of the material that limits its application.

Another type of 100% recycled plastic lumber is composite lumber. It is produced by combining plastic waste with wood shavings and sawdust.[119] The combination of wood fibers and polymers provides better properties than pure plastic lumber. The wood fibers provide a higher tensile strength than that of plastic lumber, and the plastic protects the wooden component from moisture, which

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[118] Meg Calkins, 390.

[119] "Recycled Plastic and Composite Lumber," Build It Green, October 17, 2007, www.builditgreen.org/attachments/wysiwyg/3/Recycled-Plastic-And-Composite-Lumber.pdf (accessed October 3, 2011).

helps to improve the durability of the material. Some companies, like MINIWIZ, propose further study of the structural qualities of composite plastic lumbers.

3.4. The Potentials of a Recycled HDPE Bottle

The milk bottle is a translucent HDPE bottle (see Fig. 37). Here, it is used to show the potential of transforming HDPE bottles into functional pieces in a household setting.

HDPE is used for milk containers because it has the advantages of being water resistant, toxin-free, lightweight, and relatively strong. More importantly, it beats other types of plastic because it does not favor the milk. Meanwhile, there have been efforts to reduce the ecological footprint of the material. For example, Saudi Basic Industries Corporation (SABIC) has developed an HDPE that emits about 40% of the CO^2 compared to PET, the most common food beverage plastic (see Fig 38).[120]

Figure 37. HDPE one-gallon milk bottle

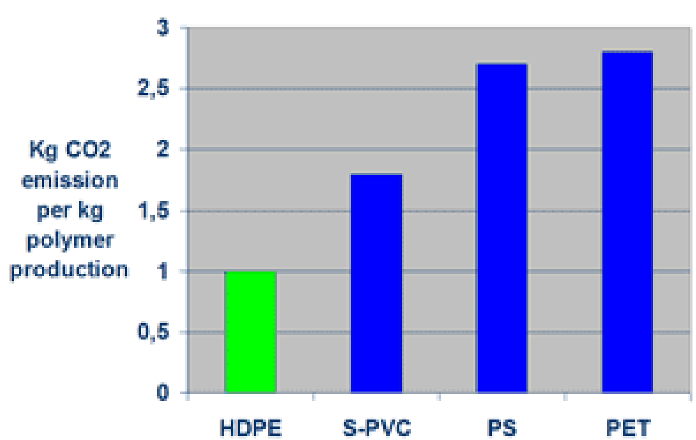

Figure 38. SABIC® HDPE Material has lower CO^2 emissions

[120] "Plastic milk bottles go greener." Saudi Basic Industries Corporation (SABIC). http://plastics.sabic.eu/cases/_en/plastic-milk-bottles-go-greener.htm (accessed November 1, 2011).

3.4.1 High Efficiency of the Milk Bottle Form

The milk bottle studied in this thesis is the one-gallon size. The weight and pressure of the milk is much higher than those in a water bottle. Because of the careful design of the bottle form, a 34-gram bottle can hold 8.5 pounds of milk. The strength of the bottle does not come from its thickness but its three-dimensional curvatures. While cylinder is the most commonly used form, the milk bottle adopts an octagonal based geometry for the convenience of transportation and storage. Four sides of the octagonal base are long, and the four adjacent sides are short, forming a shape similar to a square. The bottle gets narrower as it goes higher, and the four narrow sides gradually merge with the wider sides. Although the bottle base is a symmetrical shape, none of the four main sides of the bottle is the same. Two sides of the bottle are connected to the handle; one side has a recessed circle that is believed to enhance the strength of the bottle; and the fourth side has a smooth surface.

The handle is another strong part of the bottle. Like the sides of the base, the handle portion has a rough surface while the rest of the bottle is smooth. The handle is in the form of a tube that connects to the bottle at both ends. It makes the bottle form highly irregular, but it also presents opportunities for designers to play with the unique form to obtain a new pattern.

3.4.2 Limitations of Milk Bottle Recycling

One of the biggest reasons for the low recycling rate of milk bottles is their irregular form, which allows for maximum strength obtained from the thinnest bottle wall possible. A variety of curvatures, angles, and thicknesses are used to create a stiff bottle structure. Meanwhile, the irregular shape leads to a lower recycling efficiency during the reclamation and transportation processes. The volumes of the bottles are inconsistent, which makes a systematic and space-maximizing arrangement challenging.

3.4.3 Manual Recycling of Milk Bottles

One of the most straightforward ways to reuse the bottles is to cut and glue them. The thin walls of the bottle make it very easy to manipulate. Both the smooth and rough surfaces are easy to cut and fold. However, the softness of the thin HDPE is also a challenge when transforming the bottle. Since the interaction among the curvatures of the bottle is the main factor of its strength, the bottle becomes vulnerable if any part of the bottle is trimmed. Although it is easy to break the bottle apart for transformation, it is difficult to re-establish stiffness with the soft bottle walls.

Some other HDPE bottles, like laundry detergent bottles, are stiffer and thicker (see Fig. 30). Therefore, the bottles are harder to trim, but they maintain more strength. For these stiffer bottles, it takes much more energy to transform them and may require mechanical processes.

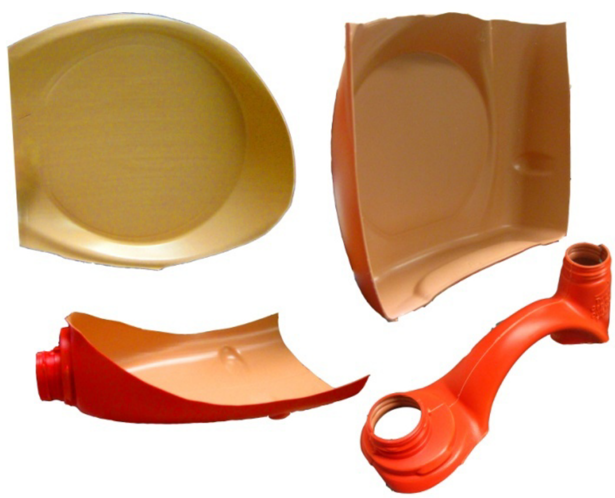

Figure 39. Laundry Detergent Cut Out. Source: Author, October 23, 2011.

Other common household HDPE bottles on the market include cleansing liquid packaging. The wide range of brands and products allows numerous forms and bottle sizes. In most cases, the bottles are made in irregular forms in order to provide maximum strength with the thinnest profile. In many cases, the bottles are asymmetrical in form and inconsistent in thickness. Therefore, the reuse of household HDPE bottles is challenging.

Many current projects utilize repetitive bottle pieces to create unique patterns for household objects like lighting fixtures, chairs, planters and dividers. The translucent characteristic of some bottles is utilized to create lighting effects. However, all of these practices are labor-intensive. From cutting and placing to gluing and finishing, every step involves delicate work, which cannot feasibly be done by machine. Therefore, the following design will aim at a relatively simple installation.

Conclusion

Both HDPE building materials and household bottles have properties that allow for great performance in various applications. There is a potential for recycled bottles to be transformed into new products that provide more functions than HDPE building materials. Depending on the available technologies, the recycled products can be created in any form that suits the requirement.

Chapter 4 Finding an Appropriate Recycling Method for Hawai‘i

To showcase the properties of recycled HDPE material, a design needs to present the recycled material in a more tangible way than carpet or composite panels. The design determines whether the product presents the features of the material, and the recycling processing affects the direction of the design.

The recycling condition in Hawai‘i is much more restricted than many other states in the US. Plastic products are made from recycled plastic pellets created on the mainland or in China, because there is no local recycling processing. Although mechanical recycling is realistic and efficient for producing a new design product, this type of business does not exist on the islands. Minimal reuse is an alternative. It is energy- and resource-conservative but time-consuming and labor-intensive. The selection of recycling methods is an important decision, as it decides the direction of the design. By listing the major constraints of local plastic recycling, the thesis discusses how these constraints affect the design process and potential solutions to the problem.

4.1 Transitional Period

While discussing the possibility of bringing plastic waste recycling to Hawai'i by expanding its application, some may question the necessity and environmental benefits of a further introduction of plastics into the building sector, in addition to pipes and windows. After all, plastics represent petroleum resources and a great amount of energy involved in their processing. Therefore, no matter how hard the industry tries to improve efficiency by increasing recycled content and lowering energy consumption, the existence and usage of plastics is considered a source of the pollution.

The ideal of zero petroleum is unlikely. No one can deny the important role that plastics play in our current lives nor can anyone prove the absolute sustainability of any other material. Therefore, it is unrealistic to ignore the value of plastic in people's everyday living. Instead of concentrating on the negatives, it is more important to develop constructive solutions which enhance the positives and reduce the issues.

4.1.1 Demand for Full Recycling

Theoretically, there are two possible futures for plastics as the already exhausted supply of petroleum resources on the planet slowly vanishes. One is that scientists ideally discover a substitute polymer from the byproducts of some processing. However, creating new polymer resources does not solve the existing plastic waste problems, and they will probably still end up in the H-Power plant as fuel.

The other possible future is a fully recycled process. This is the only solution that kills three birds with one stone. First, the plastic waste problem will be dramatically reduced by reclamation. Secondly, the petroleum extracted to produce plastics will be reduced. Last and most importantly, the resources available to recreate plastic products will be locally accessible. Depending on the regional consumption, the majority of the demand will be fulfilled by locally recycled plastics, which may lead to a shift from an import-based to locally-supported industry.

Although a great amount of energy can be conserved by switching from new material production to recycled material handling, the fully recycled process is undeniably energy consuming. Nevertheless, reclamation, recycling, and reproduction work together. The embodied energy of the products will be greatly reduced, and with carefully designed integration, it is possible to achieve an almost net-zero system. Various industries, especially food packaging and construction, are making enormous efforts to start their production with recycled waste and to end with recyclable products. Since the recycling trend began increasing in the 1960s, rapidly updated technology and advanced equipment have allowed increasingly mature conditions for an environmentally friendly system to be realized.

4.1.2 The Transitional Period

Despite the environmental demand, available technology, and low required skill set for plastic recycling in Hawai'i, local recycling facilities and programs, once beloved by the state's environmental, governmental, and professional sectors, will not return without certain changes. Meanwhile, the creation of plastic waste has not decelerated.

While the maturity of plastic recycling in Hawai'i will take years to achieve, there is a transitional period. The presented design may not be based on the existing technology in Hawai'i; however, it is designed to be flexible for future improvement and alteration. Since this thesis assumes a fully-recycling future, the design tries to utilize every part of a bottle, so that no leftovers go to the waste stream.

4.2 Decision between Minimal and Mechanical Recycling

Chapter 1 explained that the fundamental issue with mechanical recycling in Hawai'i is the imbalance between the limited plastic waste collected and the high demand for waste bottles in one dense recycled product. This fact leads to the question of whether minimal recycling reuse is more feasible than mechanical recycling, which already failed in Hawaiʻi.

The main goal of this project is to design a recycled unit that achieves a balance between restricted mechanical recycling and highly labor-intensive reuse with the existing technology and equipment in Hawaiʻi. By analyzing minimal and mechanical recycling, this study seeks a recycling method that is suitable for Hawaiʻi. It is also expected to point out what alterations are needed to increase the viability of the chosen method.

4.2.1 From Mechanical Recycling to Minimal Transformation

Zero-waste processing is an ultimate goal of many plastic recycling practitioners. The current zero-waste system of plastic industries is roughly: sort, bale, clean, grind, melt, decontaminate, squeeze into pellets or spun fiber, melt, and remold into new products. However, the steps from grinding to squeezing are not currently available in Hawaiʻi. Thus, the design needs to not only avoid the process of shipping the bottles out of the islands but also the two melting and molding processes. The reduction of recycling steps not only improves the viability of local processing under existing conditions, but also creates a higher level of sustainability by decreasing energy consumption.

Zero-waste is currently a unilateral concept, like many other sustainability-oriented slogans created for marketing purposes. In order to take a further step toward sustainability, the waste and energy issues of plastic waste transportation, sorting, and the two stages of melting and molding need to be solved. All types of processing create byproducts and consume energy. Nevertheless, this project is pursuing a relatively efficient recycling method with adaptable characteristics of mechanical recycling and reuse.

One solution is to abandon mechanical recycling processing and to replace it with minimal transformation through simple cutting and joinery. Minimal recycling is not restricted by the available facilities like mechanical processing. It allows the recycling chain to be simplified into sorting-cleaning-decontamination-cutting-folding-assembly. The majority of these steps involves relatively low energy consumption because of the elimination of melting and crystallization. Besides, the whole cycle requires only local transportation, which greatly reduces energy consumption and pollution. The cutting can be simple enough to be executed by existing machines. Meanwhile, cutting and folding allow the flexibility of joint design, which tie the bottles together and create alterable configurations of the recycled bottle layouts for a variety of functions.

Another advantage of the minimal transformation of recycled bottles is the maximum potential of post-consumer waste with the minimum carbon footprint. But it also faces the issue of intense labor demands, which significantly increases the cost and decreases efficiency. To reduce variables and increase manufacturing efficiency, a modular design is necessary, since it requires less machine types and steps. Modular units also simplify the design and production processes.

4.2.2 Utilization of the Original Bottle

Since the project aims to develop a unit based on the simple reuse of bottles, it is important to maximize the utilization of the original bottles. Bottles are commonly adopted to create lamps, simple planters, storage containers, and so on. If bottles are expected to carry out more tasks in this project, they need to be more precisely trimmed, carefully connected, securely supported, and aesthetically pleasant.

The form of the bottle is carefully studied to determine feasible and efficient trimming methods. The geometry of different parts of the bottle body will be crucial to the design of connection and assembly arrangement. It is especially important to present the characteristics of the material, since current HDPE plastic lumber does not utilize all of its features such as its light weight, flexibility, and high impact strength. With the properties of HDPE material, it is possible to design a product that minimizes the adoption of external elements, such as glue, nails, and steel plates. Therefore, the recycled HDPE bottle will be studied carefully to discover the potential of recreating a new product without machines, which determines whether HDPE post-consumer wastes are suitable for minimal recycling.

4.3 HDPE Milk Bottle Analysis Inspired by Case Studies

Although the case studies in Chapter 2 discussed different materials from HDPE containers, such as paper tubes, PET bottles, and HDPE composite, the flexible alteration of the materials and their assembly systems showed the balance between practicality and innovation. This information inspired the upcoming design to utilize the advantages of the material, by establishing proper functions and forms that emphasize and enhance its characteristics.

Compared to other plastic bottles, HDPE milk bottles face a huge challenge. The simple reuse of the bottles is limited on both industrial and family scales. Like shampoo bottles, laundry detergent bottles, and other HDPE containers, one-gallon milk bottles are not widely reused or recycled. While lacking recycling facilities are a major factor, the irregular form of these bottles is another reason for their low reuse rate. Among all of the HDPE bottles, the milk bottle probably has one of the most complex forms because of its thin wall for a high capacity. The complexity of the bottle form could be both a constraint and potential for design. Which parts to remove, alter, or preserve is an important decision. With some case studies as reference, the HDPE milk bottle form will be studied to see whether it can provide basic functions in the application, especially without machines.

4.3.1 Minimal Transformation Inspired by SOM

As introduced in Chapter 2, SOM has developed a sustainable unit that reuses bottles or plastic bags in concrete slabs of construction. The Sustainable Form-Inclusion System requires zero reformation of the bottles, and the assembly process barely requires connecters. The rebar and ties that group the bottles together are also originally part of the concrete slab. This is a good example of minimal recycling that achieves maximum efficiency with minimum alteration.

Minimal transformation is not only crucial to the emphasis on low consumption and high efficiency, but it is also the best way to present the advantages and wisdom of the original object. The preservation of the bottle, even if just partial, shows respect to the recycled object, and also plays an educational role. Ideally, the milk bottles will to undergo a minimal transformation that takes advantage of their original form and material. Analyzing the form of the milk bottle reveals the feasibility of their reformation and reassembly for a new function.

❖ HDPE Milk Bottle Form

According to bottle trimming experiments, there are three main portions of the bottle which differ in thickness, curvature, stiffness, and geometry (See Fig. 40). The bottle can also be divided into the upper and lower halves.

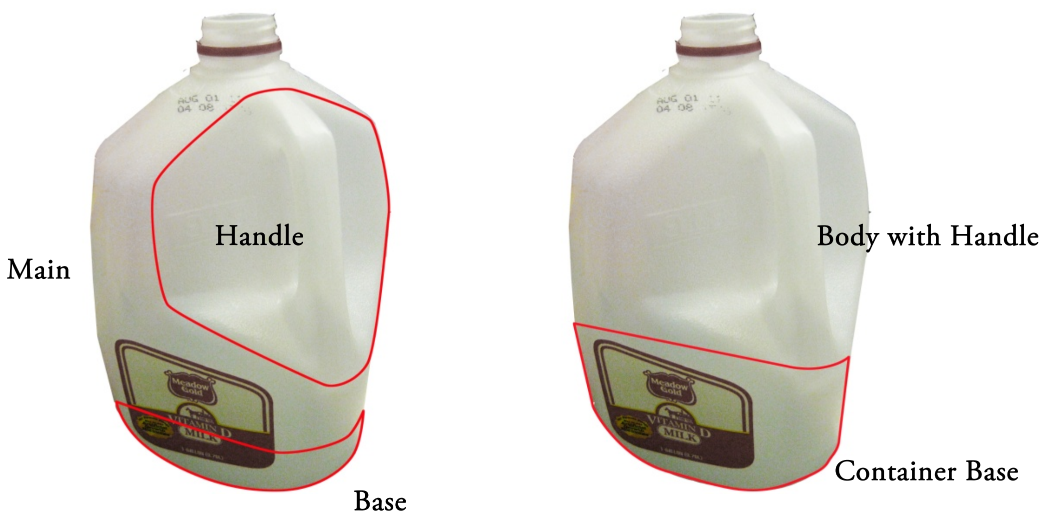

Figure 40 Two main types of divisions of a milk bottle. October 23, 2011. (Photo source: author)

The form of the milk bottle is highly asymmetrical and irregular. Each of the four sides of the bottle is different. Also, the two halves of the handle rest at different heights on the bottle, although it seems symmetrical. The irregularity of each portion is a result of a careful design that aims to achieve high capacity with the thinnest material possible. The figure below shows the usable surfaces of the bottle after the handle is removed (see Fig. 41). Each of these surfaces has its own character and function. The recessed circles, pyramid-based volume, handle, and cross-channels set on the bottom are used to create three-dimensional strength. (See Fig. 42)

Figure 41 Expanded milk bottle body and base without handle, October 23, 2011.
(Source: author)

Figure 42 Bottle base, handle, and recessed circle, October 23, 2011. (Source: author)

The bottle has a square base and a body that narrows slightly towards the top. The bottom has a different thickness along the channels and the corners to provide additional strength. Maintenance of the base is suggested since it is the only surface in the entire bottle that is stiff, flat, and regularly shaped. The base has the potential to serve as the main surface of the new unit.

In contrast, the handle is the most irregular shape in the entire bottle. It consists of a hollow tube that is angled to coordinate with the bottle form. The two ends of the tube connect to the top and middle portions of the bottle. The narrow handle is one of the strongest portions of the bottle. While it is composed of a small amount of material, the angle and curvatures create a strong frame for half of the bottle. Although it is carved out of a big portion of the bottle volume, the handle and the empty area achieve a proper balance between functionality and material efficiency.

While the handle secures two of the four sides of the bottle, there are two other surfaces that are not directly supported by it. The plain surfaces of the bottle wall are thin and soft. The design solves the issue by the angle and curvature on the corner and tops of the sides. Also, one of the surfaces, a recessed circle, is integrated to enhance the rigidity of the bottle.

The whole bottle is carefully designed. The curvature, angles, and linear bracing are the major measures taken to reinforce the strength of the bottle.

While the complex curvature and asymmetry are the major strength factors, they are also the main challenges of reassembling the bottles without major reformation. Based on the division shown in the image, the trimming process seems too difficult to do mechanically and too time-consuming to be done manually.

Therefore, although the bottle form is a helpful source of inspiration for efficient design, it is not a mass-production-friendly, post-consumer product without mechanical facilities.

4.3.2 Flexible Joint Inspired by Shigeru Ban

While the bottle form has low mass-production efficiency, the geometry of the bottle needs to be taken into further consideration. Whether bottle portions can provide potential joints is important in determining if minimal recycling is beneficial to the installation of this recycled product.

In Fig. 43, the bottle handles are cut out and glued together. The bottles can be easily connected with fixed joints, such as glue and bolts. However, it is difficult to create connecters that allow the pieces to be flexibly connected and reassembled. The form of the bottle parts creates problems with functionality and alternative assembly. Meanwhile, the production of the divided pieces is a highly labor-intensive transformation, which conflicts with the idea of efficiency. Therefore, although a flexible joint is an ideal element in a design, it is not applicable in the minimal recycling of HDPE milk bottles.

Figure 43 Bottle handles connected with fixed joint.
Figure 44 Bottle necks connected to form a dome.
October 23, 2011, (Source: author)

4.3.3 Bottle Arrangements Based on Bottle Forms Inspired by MINIWIZ

In the assembly design, bottle arrangement depends highly on the bottle form. Refugee housing has been built using glass and PET bottles. For example, MINIWIZ utilizes the geometry of Polli-Bricks to create an interlocking system. However, HDPE milk bottles cannot be used in the same way. Hence, there needs to be another way to assemble the bottles.

Milk bottles do not have self-locking characteristics. Moreover, as mentioned before, the irregular form of the bottle increases the difficulty of creating a tightly attached unit. Therefore, the assembly in this project does not focus on the air- or heat-tightness of the installment. Instead, it focuses on how to utilize the geometry of the bottles to create an interesting and aesthetic pattern that provides a function.

In conclusion, the initial approach of minimal reformation faces challenges from the bottle form in terms of layout, connection, and function. Therefore, minimal reformation, which is cutting and folding, is not suggested for the mass civil recycling of HDPE bottles.

4.4 Reconsideration of Mechanical Recycling

The balance between feasibility and existing resources is one of the biggest challenges in the design phase. To achieve a relatively realistic decision making process, a study is conducted to discuss the relationships among the three major approaches outlined in the beginning of the chapter.

Since minimal transformation seems challenging for local technologies and mechanical recycling is required to effectively recycle the HDPE bottles, how the product design can increase the feasibility of mechanical processing becomes the next question.

4.4.1 Approaches with Limitations

In this project, the sustainable product is pushed beyond upcycling, trying to achieve a relatively comprehensive sustainability. The sustainability includes energy efficiency, cost efficiency, and trash reduction. There are three approaches that this project tries to achieve (see Fig. 45):

- Mass production
- Local process
- Upcycling

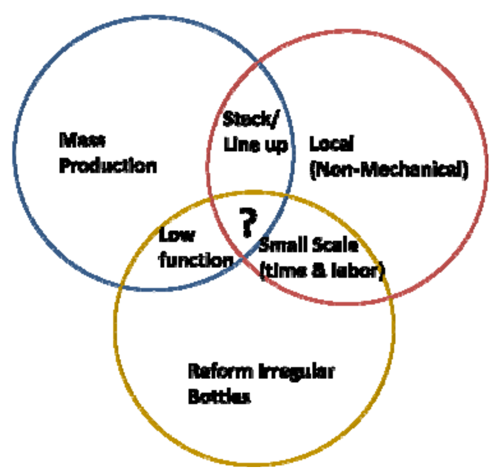

Figure 45 Three approaches of product (Diagram source: author)

- **Local Process**

From trash to a recycled product, some practitioners provide a full-cycle service, reforming a product from post-consumer waste and reclaiming the used product for reprocessing. On the other hand, many recycling facilities are separate from production processing. The recycling facilities turn the waste into clean materials provided in a universal form—pellets, while another facility remolds the pellets into new forms.

The latter system represents the current process in Hawai'i. The recycled bottle manufacturers remold the pellets shipped from the mainland into food packages. The lack of recycling equipment is the biggest problem in local plastic recycling industry. The local recycling and manufacturing companies in Hawai'i are very limited. The leading plastic companies, such as Min Plastics & Supply Inc. and Pacific Allied Product, import all of their plastic sheets and pellets because there is no recycling equipment available on the island of Oahu.[122] Ever since the closing of Reynolds Plastic Recycling, both the plastic business and the government have lost faith in local plastic recycling, mainly because of the shortage of plastic waste supply.

Therefore, recycling faces a huge technological barrier. Manual recycling seems to be the most viable recycling method, but it is highly time consuming and labor demanding, which also conflicts with the second approach of the design project: mass production.

- **Mass Production**

Mass production, with a proper market, allows the product to be more cost efficient than custom made. Not only does it pay off in terms of development cost, but it also lowers the price of the product, in order to compete with imported ones. Mass production normally requires facilities to process the material automatically, allowing for quantity and precision. According to a staff member at Pacific Allied Product, each plastic has specific requirements, which makes mass production highly efficient for each mechanical and technical setting.

If mechanical recycling is proposed to manufacture the product designed in this project, injection blow molding is likely to be adopted in order to fulfill the three-dimensional free form of the module. Unlike extrusion molding that extrudes a two-dimensional section into

[122] Min Plastics & Supply Inc. and Pacific Allied Product, Interview by author, Phone interview, Honolulu, March 16, 2012.

a desired length, injection molding is restricted to a certain length, depending on the machine and mold. According to Quick Parts, a standard mold size can be as big as 36"x36"x15", and there is no specific limitation on the geometry. However, a design with walls of the same thickness is more efficient than a design with sections of different thicknesses.[123] Also, the thickness of the ribs should be 60% of the wall.

A mechanized production process allows the design to be relatively complex and precise, to include locks that allow the unit to be joined together. With a proper design, the self connections can decrease the cost, material, and time required to install units with an external item. These features will not be satisfied by manual recycling or minimal transformation. To bring mechanical recycling facilities back to the State of Hawaiʻi, the recycled products need to have a much higher positioning in the market.

❖ **Upcycling**

Upcycling is increasingly emphasized in the recycling industry. Upcycling generally aims to utilize post-consumed materials to regenerate new products of higher values. The properties of the material are part of the "up" and are better presented in the new product . Maximizing the capabilities of the material is an important consideration in the design, which includes form, color, and application.

If the properties of the material need to be improved for certain applications, the qualities are modified through mechanical processing. The common and stable way to achieve this is to put in a highly controlled amount of qualified additives, so that it provides the desired properties without sacrificing the safety of the material. Precise additives and temperature control are crucial to the improvement of materials in the upcycling process. Therefore, mechanical recycling is effective in giving new life to post-consumer waste.

[123] See Appendix C

4.4.2 Necessity of Mechanical Recycling

Manual recycling cannot manipulate some factors such as temperature. When a milk bottle is heated, it gets softer and becomes transparent. When the temperature reaches a certain point, the plastic melts into a clear thick liquid, which can be easily formed into other things. In Fig. 46, a milk bottle is melted by a candle (see Fig. 47). In comparison, a lighter melts a milk bottle much faster than the candle, but it also leaves some burnt marks. Therefore, HDPE material needs professional devices that precisely control temperature and time, so that it does not impact the properties of the material.

After milk bottle pieces are completely melted, they become a pile of clear gel, but in the absence of heat, the gel turns into a piece of solid white plastic again (see Fig. 48). The burn mark created from the high temperature tends to stay after it cools down as well. The experiment proves that temperature control is very important during the process.

Figure 46 Milk bottle becomes translucent over a candle, December 4, 2011 (Source: author)

Figure 47 Milk bottle melted by a lighter, December 4, 2011 (Source: author)

Figure 48 Before and after the melted milk bottle cools, December 4, 2011 (Source: author)

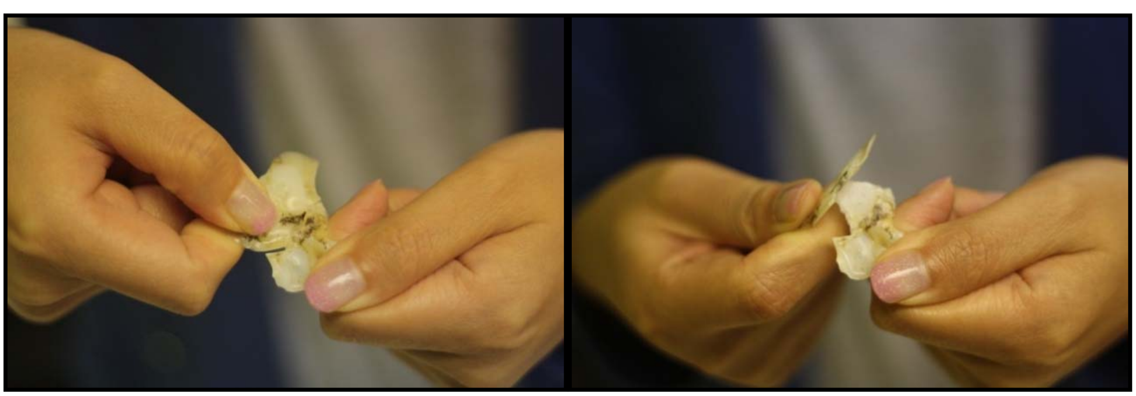

Figure 49 After cooling, the melted milk bottle piece is solid but brittle, December 4, 2011. (Source: author)

Figure 50 When slowly heated, the milk bottle pieces become solid, shiny, and brittle, December 4, 2011 (Source: author)

In addition to the temperature, the properties changed during the heating process are also difficult to control without specific knowledge and precise measurement. In Fig. 49, the images show the loss of tensile strength after melting. The reformed piece is easily cracked by hand. When HDPE is processed mechanically, the temperature is carefully monitored, and a proper amount of tensile agent is added in order to provide the ideal function.

In Fig. 50, the milk bottle pieces are evenly placed over the fire. The low heat helps the HDPE to melt relatively evenly and smoothly, which prevents discoloration. There is only one spot of the melted piece that presents yellow mark, which is the area directly on top of the fire. The heat used to melt the plastic needs to be evenly distributed. Also, the low heat is not transmitted to the upper pieces of the pile, which implies the plastic piece is not melted with a certain thickness. The shiny bottom of the melted piece shows the possibility for the material to be reformed into any pattern or texture, and it is a fairly easy step.

In conclusion, it is difficult to reform HDPE bottles manually without sacrificing the tensile strength and texture of the material. This again proves the necessity of mechanical processing for local recycling. The technology has to be brought back to Hawaiʻi in order to allow the rebirth of local industries.

4.4.3 Mechanical Recycling for Viability

It makes little sense to develop the recycling industry in Hawaiʻi with only manual processes. Therefore, the following design will be based on mechanical recycling, which allows for a dynamic form and precise connection.

One of the biggest arguments against the resuscitation of the plastic recycling business in Hawaiʻi is the insufficient amount of plastic waste available. The following design avoids treating the HDPE like wood, which has to be highly compressed, and reduces the amount of HDPE consumed in the reduced product, allowing a low weight and high efficiency. By reducing the demand for HDPE bottles, the design increases the feasibility of bringing the necessary machines and technical resources back to the islands.

Conclusion

Because of the lack of recycling facilities in Hawaiʻi, the study proposed shifting from mechanical to minimal recycling. However, upon finding that minimal recycling is not efficient for HDPE bottles, mechanical recycling is presented as the suitable method for a civil scale of recycling.

The mechanical recycling of plastic and reduction of post-consumer resources complement each other in the process of rediscovering the proper recycling method in Hawaiʻi. Hence, the existing HDPE recycled products need to be designed based on this principle. In the coming design, the effective use of HDPE material used in the product is required to achieve a reasonable viability.

Chapter 5 Responsive Initial Design Phase

The design in this chapter aims to fulfill a series of requirements derived from careful consideration of environmental issues, material characteristics, various case studies, and production methods. The state's potential to provide locally products that have a higher value and functional performance through upcycling underscores the need for local recycling of HDPE.

5.1 Initial Design: A Modular Planter

As discussed earlier, the design is based on the potential for mass mechanical production. Although the state of Hawaiʻi does not currently have an established system to recycle plastic waste locally, this project aims to draw attention to recycled HDPE material, with proposed integration into people's everyday lives.

The modular unit is designed so that it utilizes the properties of HDPE as well as the trend of embedding multiple functions in one object. Meanwhile, the design aims at a simplicity that allows flexible configuration and assembly.

From the perspective of an indoor product, the following discussion explains why a planter pocket is selected to achieve both HDPE material representation and effective use.

5.1.1 Indoor Air Quality (IAQ) Improvement: Recycled HDPE Planter Pocket

The idea of recycling HDPE bottles emerged from a sustainable approach, and the product aims to improve people's everyday IAQ. According to the EPA website, there are three major methods of improving IAQ: source, ventilation, and air cleaner.[124]

The source of the IAQ involves building materials, appliances, and the surrounding environment. HDPE has the potential to be adopted as a safe indoor material, but it requires an enormous amount of repetitive testing, alteration, and reproduction, which will not be studied in depth in this thesis. The ventilation aspects can be effectively improved through building design and the use of fans; therefore, additional plastic is unnecessary. Finally, an air cleaner is normally an electronic device that collects indoor air and purifies it through a filter. The downside of an air cleaner is the demand for energy and maintenance.

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[124] "Improving Indoor Air Quality | Indoor Air Quality | US EPA," US Environmental Protection Agency, http://www.epa.gov/iaq/is-imprv.html (accessed March 28, 2012).

House plants, on the other hand, are a natural alternative. House plants may not prove equally efficient in cleaning some pollution, but they are known to absorb harmful elements in the air, including radiation.

In addition to the improvement of IAQ, house plants endow the recycled HDPE material with a new application in the local indoor environment. Hawai'i has the temperate weather for interior and exterior plants, and the integrated design of planters can greatly increase building users' exposure to greenery without sacrificing much space. Besides, a plant holder presents a number of characteristics of the recycled HDPE, which fulfills the basic requirements and complements the function of a planter for indoor use.

5.1.2 HDPE Characteristics for a Planter

The water and chemical resistance of HDPE allows the planter to contain dirt with moisture and nutrients. Some plastic types with relatively low endurance, such as PC, cannot endure certain types of chemicals without erosion or resolution. The characteristics of HDPE allow planter users to have more options for contents than a regularly recycled plastic bottle. More importantly, the chemical resistance helps the product to endure a large variety of cleansers. Most existing household cleaning products contain chemicals that erode plastic products. Not only does such erosion affect the appearance of the planters, it possibly also releases toxic emissions that could harm human health, especially that of children. HDPE, on the other hand, successfully allows durability with necessary maintenance.

The light weight of recycled HDPE is also an important characteristic. Conventional planters are made of ceramic or glass, which are highly durable but heavy. (See Fig. 51) Such planters may have beautiful designs and high capacities, but they are fragile during transportation. Plastic plant holders are less expensive, more durable, and lighter weight alternatives to conventional planters. (See Fig. 52) Because of their intended short-term use, the functionality and aesthetics of plastic plant holders are not considerably presented in the product. In this design, the light weight of the recycled HDPE is not the end of the story, as this characteristic allows the recycled HDPE planter to have more functions and assembly methods than conventional ones.

Figure 51 Hexagonal ceramic orchid pot[125]

Figure 52 Plastic plant pots[126]

Recycled HDPE is naturally opaque, and it comes in a large variety of colors. Many plastic types, such as PET, PC, and PP, are commonly presented in partly transparent colors, which are highly preferred for beverages. However, planters contain dirt, which impacts the appearance of the planter; therefore, the opaque colors of HDPE are preferable to maintain a consistent indoor environment quality.

HDPE has relatively high impact strength among plastics. This characteristic improves the safety of the planters for families with children. Although the planters are not designed for heavy duty uses, the impact strength prevents the HDPE planter from breaking easily, thereby endowing it with more location options than fragile plastics.

5.2 Initial Design: Form and Function

The recycled HDPE planter aims to offer strength with a thin material. Inspired by the HDPE milk bottle, the planter is designed with three-dimensional curvatures so that it obtains maximum strength. The softness of the thin material and the rigidity of the curved area create the dynamics between flexibility and strength. The softness allows the planter to be bended or folded for the ease of transportation and installation. The rigid edge and back of the planter function as its backbone and are also an ideal location for connecters.

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[125] "5" Vanilla Bean Solid Hexagon Ceramic Orchid Po," rePotme Orchid Supplies, http://www.repotme.com/ceramic-orchid-pots/Ceramic-Orchid-Pot-V2.html (accessed May 1, 2012).
[126] "10 Uses for Plastic Plant Pots." Home Improvement and Remodeling: This Old House. http://www.thisoldhouse.com/toh/photos/0,,20293256,00.html (accessed May 1, 2012).

5.2.1 Recycled Planter Pocket

The main body of the pocket is in a three-dimensional diamond form. The front side of the diamond is operable due to the flexibility of the material (See Fig. 53). The material is similar to that of a milk bottle, which is thin but malleable. The upper and lower halves of the front pocket can be bent inward toward the back, allowing the options of a semi-open pocket or an enclosed bag (See Fig. 54). The foldable feature also dramatically reduces the volume of the contents and allows the units to be stacked on each other for transportation.

The back of the pocket is more rigid than the front because of the pyramid form with curved edges. The back of the pocket is generally the support of the pocket. While the front is flexible, the back is stable so that it provides a backbone for the connected units (See Fig. 55). The back of the pocket is inspired by the curvatures in a milk bottle, which provides strength in various dimensions, and it allows the connection to be installed in the back of the bottle as well, leaving a clean appearance on the front.

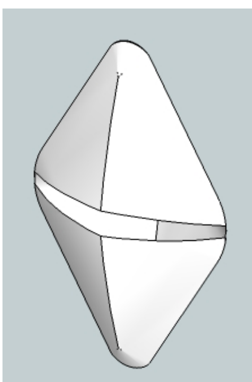


Figure 53 Front pockets


Figure 54 Pocket planter

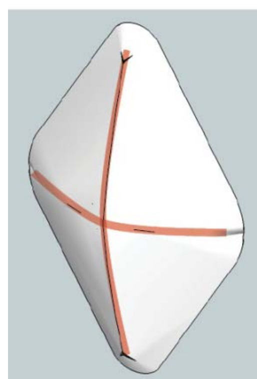


Figure 55 Curved backbone

The pocket is approximately 6" (H) x 4" (W) x 2" (D). The pocket keeps the translucent character of the thin HDPE, which allows it to participate in light transmittance in daylight or artificial lights. This characteristic allows a lighting fixture to be integrated. The pocket also allows different colors based on demand. For example, when UV-resistance agent is added to HDPE, the material tends to appear dark in color, which can be used for functions such as shading devices or outdoor wall decor. Since the material can be produced in a wide range of colors, the pocket has the potential to play with color and light, which brings a new spatial experience to building users.

5.2.2 The Connecter

While the planter pockets obtain various functions, they require external connecters for assembly. In order to maintain the simplicity of the pocket appearance, the connecters are set on the back of each pocket. The connecter is a small integrated snap that allows two units to be joined together, back to back. There are also both vertical and horizontal holes for security cables. For functions such as shading, partitioning, and lighting fixtures, the pocket does not need the thickness to provide load bearing capability like the planter. Therefore, they can be connected via cable and placed at an adjustable distance to allow various amounts of light to go through them.

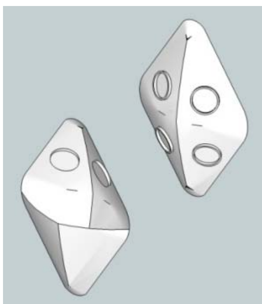
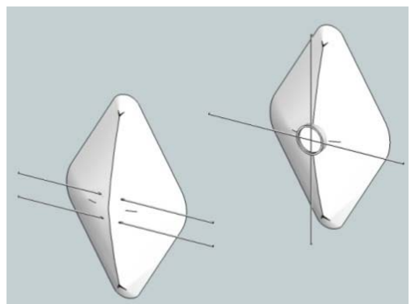
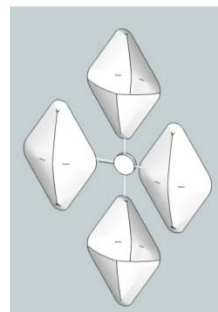




Figure 56 Surface snap connecter, Figure 57 Embedded center connecter, Figure 58 External connecter

The snap connecters allow the pockets to be joined to each other (See Fig. 56). The planters snap to each other on the back side, so that the connection does not impact the plants in the pockets. The snap connecters accurately assemble the pockets into a variety of functional combinations. The characteristics of the plastic material allow the snap to achieve a convenient and secure connection, and the connected pockets create a balance for the curved pockets.

The pockets can also be assembled with horizontal and vertical cables (See Fig. 57 & 58) that provide a stable framework for the pockets. The cables allow the pockets to be connected with an adjustable distance and angle, in order to achieve a variety of effects with the same product. The tensile structure of pocket screens allows an array of assembly combinations. With an external device, the rotatable cables can allow the pockets to turn and catch a range of shading. The cables can also create a fixed web for the pockets and create a suitable pattern for a space.

5.2.3 Various Functions with Different Installations

A number of additional functions are proposed for the planter pocket according to their installation methods. With snap cable connections, the pocket acts as a lighting fixture with lights inside by taking advantage of the semi-opaque color option of HDPE. The HDPE material has a melting temperature of higher than 212 degrees Fahrenheit, and it can endure the heat created by certain types of light bulbs. With two layers or more snapped together, the pockets can be built into a self-standing partition light wall (See Fig. 59). Pockets can be installed in different forms under various circumstances, including layers, geometry, and size. As a lighting fixture, the pocket provides a huge opportunity for users to create different effects to suit their needs and creativity.

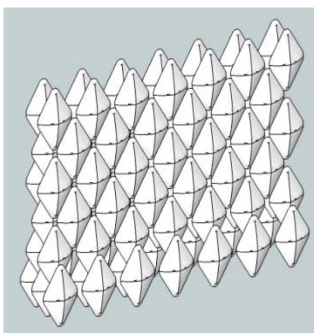


Figure 59 Lighting Partition

Figure 60 Planter Shading

The HDPE planter pocket can also be used as a shading device (See Fig. 60). Because of the light weight of HDPE, a series of the pockets can be connected to create a rotatable screen, allowing a three-dimensional texture. When rotated, the curvature of the pocket creates a diffused daylight on the screen, creating a lighting pattern that changes with the time of a day.

The three functions of the HDPE pockets, which are planter, lighting fixture, and shading device, are interchangeable due to the modular system. Users can mix three functions according to the needs of different spaces in a building. HDPE satisfies the requirements of the three functions, and helps to bring about the integration of recycled plastic and multifunctional application, achieving a high level of upcycling.

5.3 From Initial Design to Proposed Design

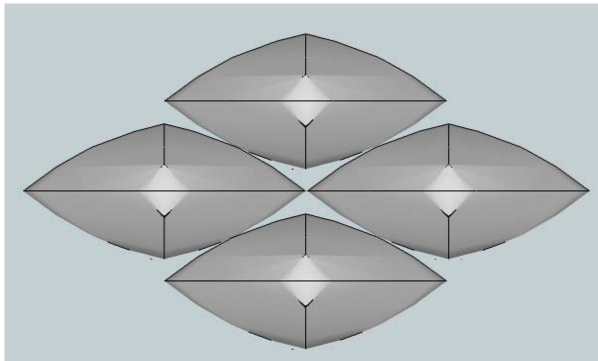
The initial design of the planter pocket responds to some of the project criteria, but there are some aspects that need to be improved. The initial design was a helpful experiment for the proposed design. The pocket addresses the major elements that will be presented in the proposed design. By analyzing the pros and cons of the initial design, the proposed design aims to achieve a balance among multiple functions, material presentation, assembly flexibility, and aesthetics. The design aims to provide an example of the integration of a recycled HDPE plastic product with an indoor space.

5.3.1 Improvement from Initial Design

The initial design is derived from a simple planter pocket that has a simple form with multiple functions. This thought, however, has limited some of the design potential. The pocket form becomes literal and inflexible under normal circumstances. The external connection required for installation is also a drawback as homogeneity is one of the biggest emphases in the project for the ease of the recycling process. In the new design, these concerns will be solved by design.

❖ **Geometries**

The straightforward design of the planter pocket utilizes curvature to enhance strength. However, the curvature also leads to assembly issues. From both top view and the perspective, the vacant volume between the pockets appears to be an inefficient use of space and form (See Fig. 61 & 62). Because of the curvature, the planter pockets do not fit together tightly, which decreases the integrity when the pieces are fit together. Since curves are highly directional and dimensional, curvatures highly restrict the form, function, and assembly of the planters, such as self-standing and interlocking features. Therefore, a new geometry is considered to achieve a better balance between function and installation.



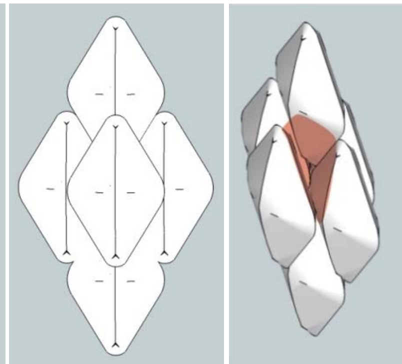


Figure 61 Gaps between pockets

Figure 62 Big gap among three planters

While curvature allows the three-dimensional strength of a form, a triangle is also considered a rigid framework. Most existing curvy building structures are achieved with a triangular-based framework. Therefore, in the upcoming proposed design, the triangle plays an important role in the structure of single and multiple planters. However, the drawback of the triangle is the shallow areas of the form, which limit the usable space.

On the other hand, a rectangular parallelepiped is considered the most efficient space compared to other volumes (See Fig. 63). Boxy spaces exist in most living environments, and they allow for furniture and decoration. However, the rectangular parallelepiped is also known for its repetitive and static characteristics. A bookshelf-like planter combination may prove efficient in spatial usage, but it does not pronounce the uniqueness of the HDPE material nor does it increase people's attention to recycled materials.

Therefore, a form with both the characteristics of triangles and parallelepipeds will create an interesting dynamic of structural strength, usable space, and flexibility. Forms such as the pyramid and diamond are taken into consideration in the potential design phase.

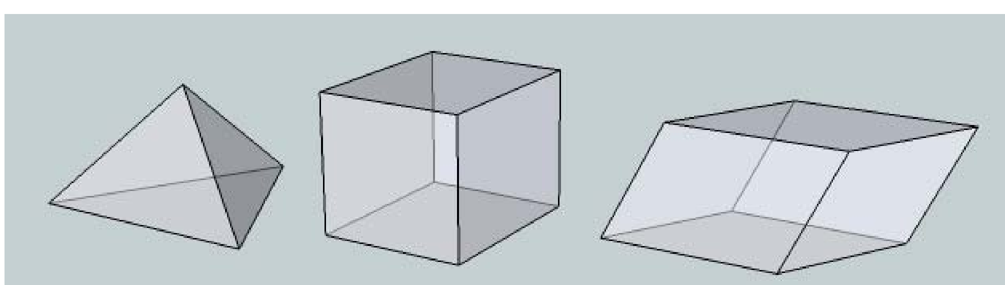


Figure 63 Geometries: triangular pyramid, rectangular parallelepiped, and parallelepiped

❖ External Connecter

Another problem with the diamond form is the external connecters required. The diamond form with curved surfaces and edges increases the challenge of embedding a connecter that allows the pockets to be interlocked.

The snap connecters are embedded in the pocket. In the center of the pocket, there is not enough thickness for the pocket wall to carry the embedded connecter. The connecters impact the form of the planter, which may greatly alter the density or volume of the pocket, causing an imbalance between the front and back of the pocket. Also, the single loading point on the pocket side may cause a deformation of the plastic, which affects the assembly of the pockets.

The cable connecter and the rotation device provide an external framework for the pockets. The metal parts are installed to ensure accurate and secure control of the placement and location of the pockets. The pockets depend on the cables to stand up, and the movement of the pockets relies on the rotation device. In this case, the pockets are highly dependent on other materials. The self-supporting capabilities of the HDPE material are not fully utilized in the initial design.

Therefore, an integrated connecter is preferred over an external one. In addition to the joinery function, the connecter also maintains the simplicity of the planter and showcases the plastic characteristics of HDPE.

❖ Options of Combination

The planter pockets are designed in a uniform prism shape. The planter is designed in a curved form to obtain strength and capacity, using a minimal amount of material. However, the complexity of the form does not compromise the ease of installation, even for people who have no experience in construction. The difficulty for installation brings challenges to the flexibly arrangement of the units. Hence, the improvement involves the alteration of planter form. One connecter with multiple installing methods or multiple connecters on one piece can be considered in the proposed design.

5.3.2 Proposed Design with Additional Functions

Although the initial design faces some critical changes, the functions of the planter pocket present the major characteristics of recycled HDPE. The planter shows water and chemical resistance as a planter, plasticity as a three-dimensional curved form, and color variety as a lighting device.

In the proposed design phase, the planter is expected to show additional features of the recycled HDPE material and to provide more features than the initial design. The planter aims to be integrated into users' everyday lives. The multifunctional character of the proposed recycled HDPE product is one of the main factors in gaining the attention of manufacturers, in order to revive the culture of recycling plastic wastes.

- **Lighting Fixture**

Lighting fixture is one of the important functions of the new proposed design. The HDPE milk bottle has shown the light transmittance of the material at a certain thickness. The lighting fixture is designed to be integrated with various interior settings, such as walls, benches, tables, and shelves. A wide range of applications is proposed to increase the adoptability of the product, which may potentially increase the demand for it and the feasibility of bringing mechanical recycling back to Hawaiʻi.

Also, lighting fixtures are commonly a separate element in everyday living. Their integration with indoor settings helps to freely locate the luminance source and level, instead of depending on ceilings, tables, and floor lamps. The new concept of luminous furniture is also inspirational for contemporary living.

- **Furniture**

By enhancing the strength of the planter, it is possible to turn it into part of the furniture. HDPE is capable of carrying a certain load with proper design and assembly. A children's playground is an example that shows the strength and durability of the material. Also, with carefully tested and controlled additives, HDPE provides durability to the product.

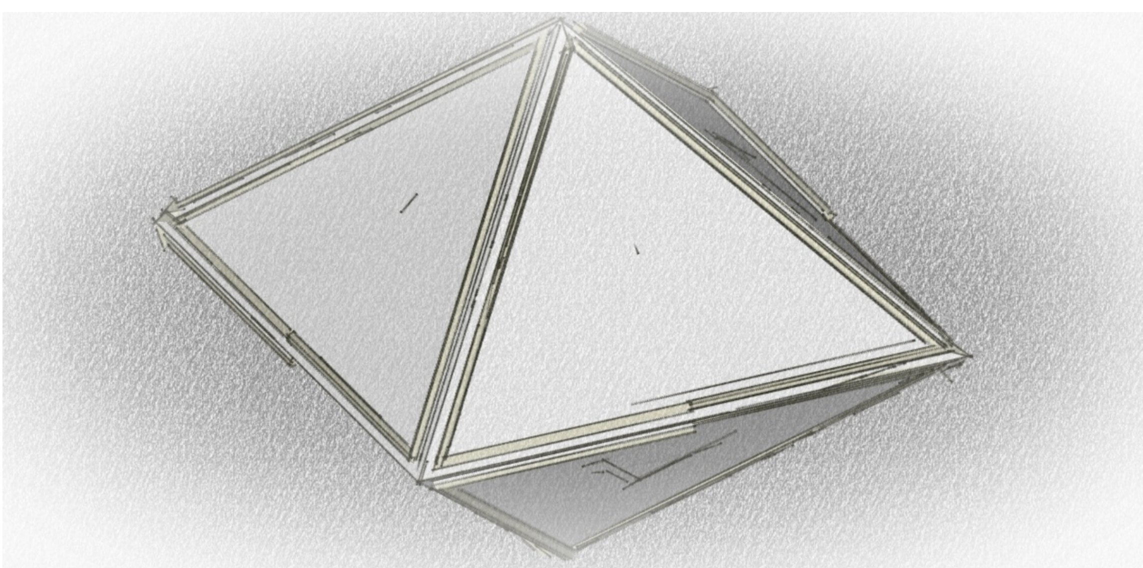
In the proposed design phase, the product is expected to perform a much wider range of functions for a higher usage rate. Tabletops, stools, light-duty shelves, magazine pockets, and other applications can be integrated by assembling the planter pieces in various ways. The emphasis on flexibility is further presented in the new design.

Conclusion

The initial design outlined the possible functions of the recycled HDPE product based on the characteristics and efficient use of the material. The initial design was conducted to achieve a better understanding of the potential and constraints of HDPE, allowing the new design to selectively adopt and discard. The initial design aims at the minimal use of material while the upcoming proposed design focuses on the balance between material efficiency and stable applications.

Chapter 6 Proposed Design: HDPE Diamond

The variety of molding processes allows plastic products to be made in literally any form. However, a fixed one-piece product highly reduces the flexibility of applications, which leads to a lower level of the reuse or recycling potential of the post-consumer product. On the other hand, a partial unit allows the opportunity of creative assembly. Starting from the simplest modular unit, the following design creates a dynamic integration among different functions through the flexible assemblies.



6.1 Design Solutions

As a conclusive design product that reflects the information discussed in the previous chapters, the product is meant to propose a possible solution to a series of concerns.

First of all, the design presents a new style of recycled HDPE product. The design tries to promote the recycling of plastic bottles by proposing a light weight piece that can be easily molded, transported, and installed in different ways to form different volumes. The modular planter is more than just a plant holder. In a modern home, it may play the role of wall partitions, lighting fixtures, and furniture. A balance among functionality, inspiration, and ease of assembly is necessary to present the design to users who desire something convenient, inspiring, and useful.

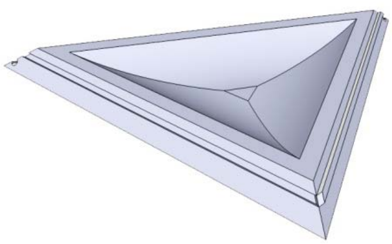
Second of all, the design will resolve some of the weaknesses of the HDPE material, as it does not require thickness or high density, such as a compressed beam made of hundreds of bottles, to perform its functions. Inspired by the milk bottle, a three-directional curved form is effective in improving the strength of the thin material. However, this type of form also brings inconvenience to installation, since the surfaces are highly irregular and direction-oriented. Hence, the design tries to obtain a balance between a flat surface that is easy to utilize and the necessary curves that add strength.

Finally, the design integrates the flexible character of polymer, which is commonly seen in buckles and bottle caps. In the design, this characteristic is presented through the joinery of the planter components, which can be self-connected without external parts. The proposed planter tries to solve installation problems without introducing another type of material, in order to maintain the homogeneity of the component, so that it can be easily prepared for recycling as a post-consumer product.

6.2 Geometry: from Triangle to Pyramid to Diamond

A pyramid provides a huge variety of form combinations, since it has both square and triangle surfaces, which create a balance between the two shapes. A rectangle is traditionally considered the most practical shape in daily life because of the usable surface area and ease of installation. The triangle, on the other hand, is beneficial for rigid structures. Therefore, the design aims to take advantage of the two shapes in order to develop the dynamics between functions.

The triangle is one of the strongest geometric shapes because of the rigidity among the three sides. This design utilizes this character as an alternative to the 3-directional curve form, trying to create a fabric that delivers the load through the connected edges.



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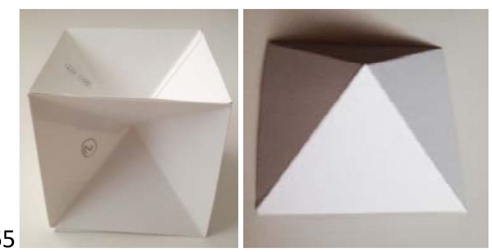

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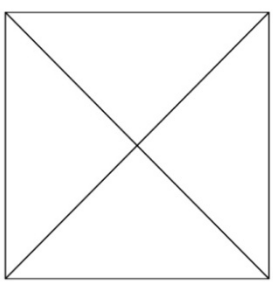

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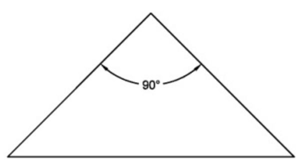

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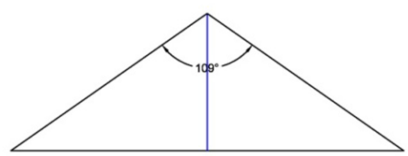

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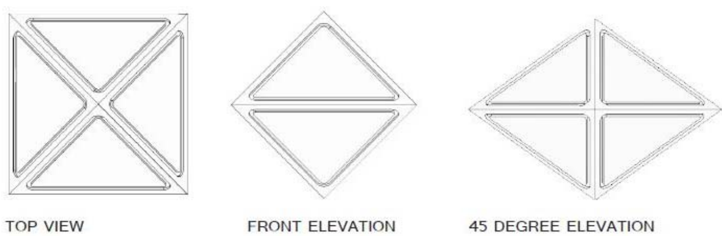
Figure 64 Design of single triangle piece
Figure 65 Four 90-degree-rotated pyramids form a cube
Figure 66 Top view of square-base pyramid
Figure 67 Front elevation of pyramid
Figure 68 Two adjacent sides of the pyramid form a 120-degree angle

The basic unit of the design is a triangle (See Fig. 64). The triangle is derived from a square-base pyramid that has perpendicular cross surfaces; each surface of the pyramid is a triangle (see Fig 64-68). The square base of the pyramid creates a dynamic basic assembly grid for the units to be put together, which lessens the confusion compared to a solely triangular grid. Meanwhile, the equal sides of these isosceles triangles will be heavily utilized as the assembling joints. It behaves as the axis for any two pieces to rotate along. Also, the equal sides have the potential to match with various sides of one volume, allowing the object to rotate along its own central axis.

Compared to a boxy form, some may argue that the pyramid is not practical because of its slopes and angles. It is true that the units will not be used in a conventional way, which merely provides divisions and consistent spaces for the objects to be placed inside. However, this pyramid unit reveals a new perspective of multifunctional planters. The unconventional style of the planter has several benefits for modern home settings.



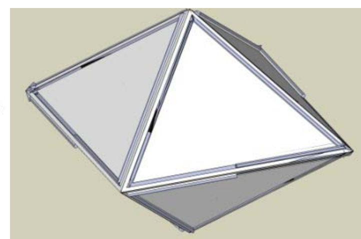


Figure 69 Three views of the diamond form

Figure 70 Perspective view of diamond

6.2.1 Combination Options

The angles of a pyramid allow alternative combinations. A cubic form, for example, has right angles at all the corners, which gives it very limited options for the placement of adjacent pieces. The consistent relationship between pieces gives the combination a static result in terms of rotation and movement. However, if the form provides more than one option of conventional angles, such as 45 or 60 degrees, the combinations show a much richer variety.

In this project, the common form in the design is a diamond created by two pyramids (See Fig. 72). The diamond form allows a considerable volume and has eight repetitive surfaces. However, they are also highly directional, as the smaller angle of the triangle shall face the tip of either pyramid. The directional character of the assembly brings both freedom and restriction to the composition.

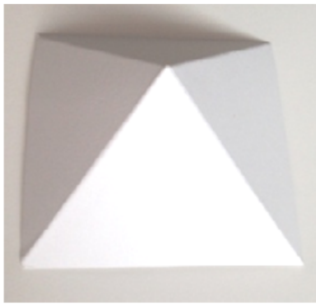


Figure 71 Square-base pyramid

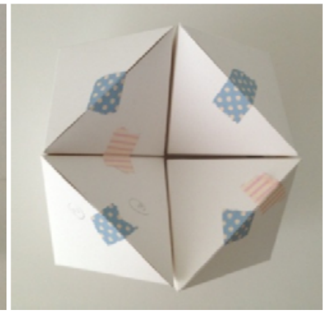
Figure 72 Diamond form composed of two pyramids

❖ Square Group

This group utilizes the right angle of the pyramid elevation. When two pyramids are put together, they form a 180-degree angle; a 360-degree angle is formed with four of them. This character helps to compose one of the combinations of the units: the square group. This group can be simply assembled with a minimum of four pyramids. The recessed pyramid on the top is a very straightforward container for plants or other objects. The loads are transferred through the sides of the pyramids, which also emphasizes the importance of their strength.

However, the four sides and the bottom of the pyramid square group are not properly utilized. When the pyramids are replaced by diamond forms, a different square-based group is created. This group allows the four sides of the group to have volume, which can be utilized for plants, storage, lighting, and so on. This group can be placed either vertically or horizontally. Because of the flat surfaces around the four sides, the group can be placed individually or in a group.

The square group can also be altered by adding more diamonds to it. For example, when six diamonds, located on four sides, one top and one bottom, are assembled, a ball with twelve prismatic surfaces is formed, and it can be creatively utilized.

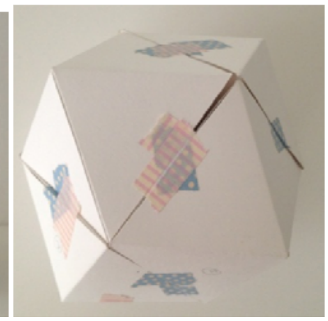



Figure 73 Square group composed of four pyramids
Figure 74 Top view of square group composed of four diamonds
Figure 75 Side view of four pyramids
Figure 76 Five diamonds
Figure 77 Six diamonds

Figure 78 Perspective, diagonal elevation, and front elevation views

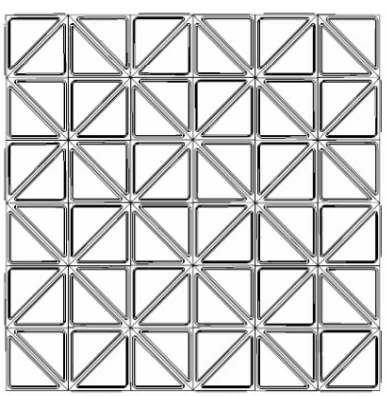
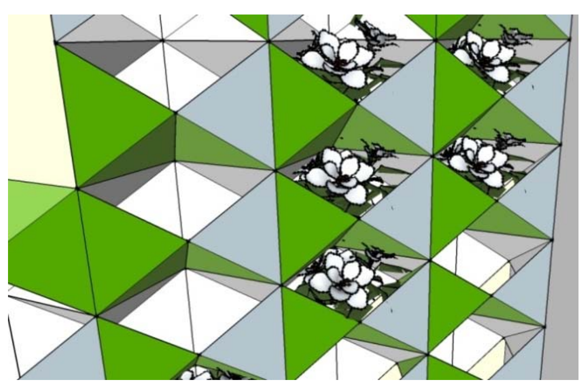



Figure 79 Vertical layout
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Figure 80 Example of vertical usage

❖ Hexagon Group

The hexagon group, unlike the square group, requires a diamond unit as it takes two pyramids to form a 120-degree angle. The orientation of the diamonds is also different from the square group. The hexagon group starts with two diamond units that are assembled together. These two diamonds are rotated along the longitudinal axis, and the first two vertical surfaces that come up form a 120-degree angle. Six diamond units form a recessed hexagon in the middle. The six altered pyramids are irregular and difficult to assemble with another hexagon group. However, a prismatic composed of two triangles can fill up the gap between two hexagon groups.

The hexagon group presents limited horizontal or vertical area, but the angles that it creates provide plenty of opportunities for users to alter the volume and function by making openings. Also, the hexagon shape makes the group circle-friendly, so this group can be integrated with circular elements, such as glass tabletops.

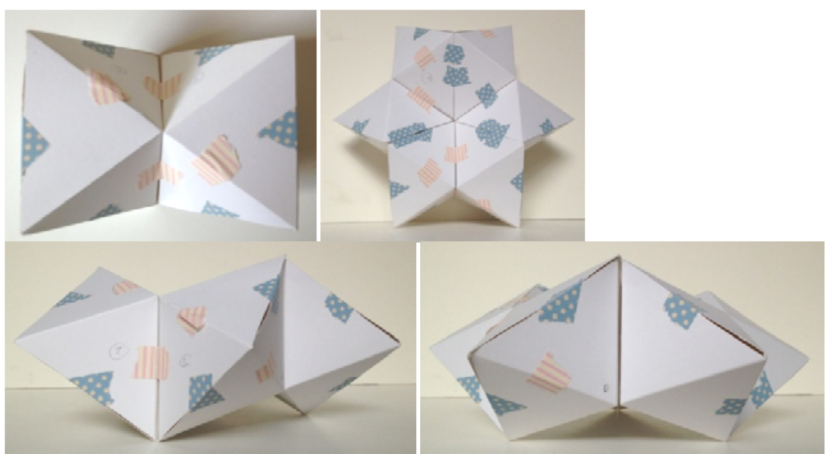
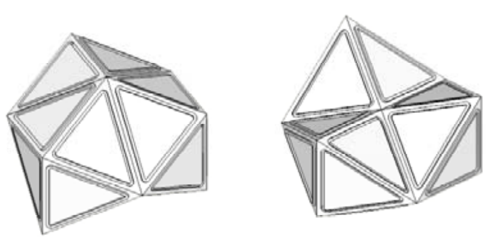


Figure 81 Hexagon group composed of six diamonds



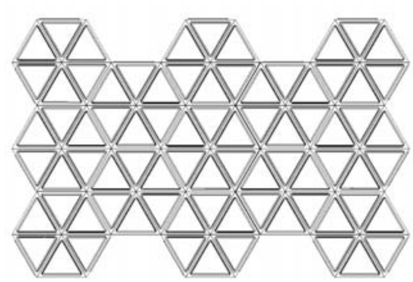


Figure 82 Perspectives of hexagon group

Figure 83 Vertical layout of hexagon groups

6.2.2 Flexible Installation and Functions

The rotation of the pyramid allows the combination to have different angles and slope. However, this may be beneficial or inconvenient for the installation. The application of the planter components are highly related to their geometry and orientation.

- **Flat top**

A good example of the flat top unit is the single diamond unit. No matter which surface is placed on the bottom, the top surface is always parallel to the bottom, making it a horizontal top. The horizontal flat top allows a huge variety of object functions, such as tabletop, shelf, and stool. A flat top is friendlier to work with than an angled top.

Figure 84 Flat surfaces

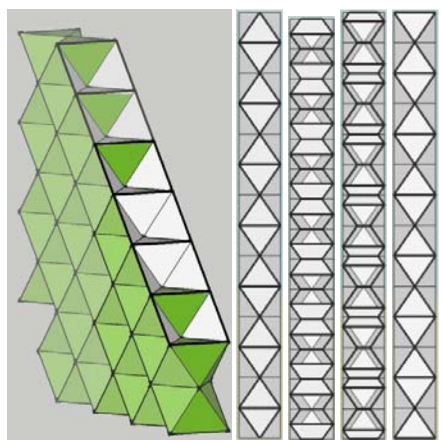


Figure 85 Section looking down at the flat surfaces

The variable space inside a diamond differs greatly from that within consistent and conventional rectangular grids. It is undeniable that the usable space in the diamonds is less practical under normal circumstances than a regular shelf, but the diamonds are not meant to be merely a shelf. Instead, it is a multifunctional setting that attracts people's attention and integration with the household object. The HDPE diamonds reflect the emotion, character, and imagination of the users, which give it a lively meaning in the space.

Figure 86 Stool and tabletop with magazine pocket and planter pocket

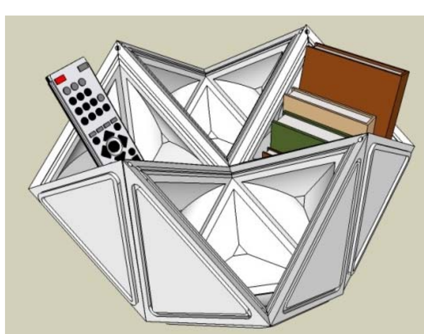


Figure 87 Tabletop container

Figure 88 Light-duty shelf with planter

❖ Flat and Rough Sides

When the side of the diamond is vertical, it provides a smoother and more prominent surface for both installation and usage. This kind of installation is beneficial for usage like shelves and vertical planters. For indoor environments with children, the flat surface can also prevent potential injury caused by a rough surface. The flat side is also beneficial for placement against walls or other flat surfaces.

On the other hand, the hexagon groups form a relatively rough surface, which may provide an interesting texture for the spatial experience. In sunlight or artificial lighting, the angled surfaces reflect the light at different angles, creating an interesting diffused light for the space.

Users can use both of the surface textures to create a unique and personal space according to their demands and creativity.

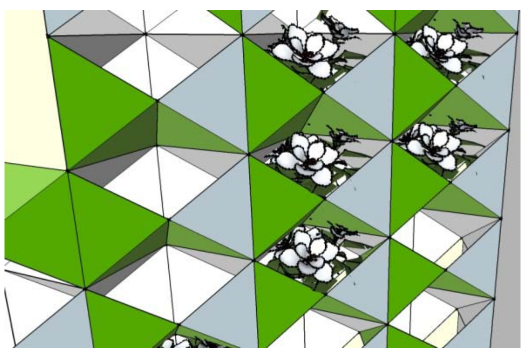


Figure 89 Planter wall with flat surface

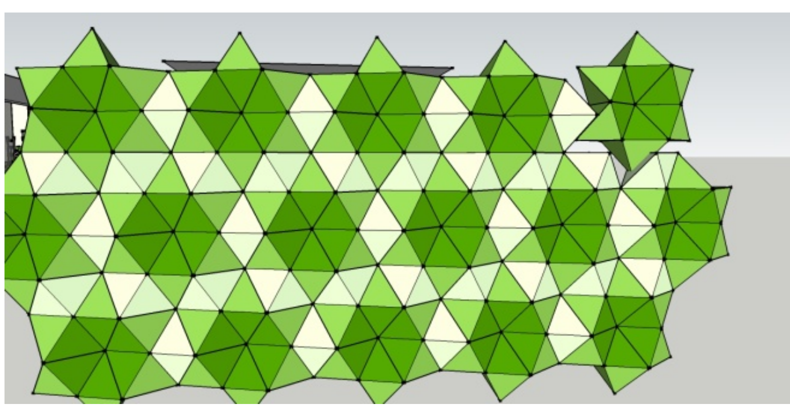


Figure 90 Hexagon group with rough surface

❖ **Rendering**

Figure 91 Living room partition: integration between planter and lighting fixture

Figure 92 Dining area: vertically grouped

Figure 93 Kitchen table planter: vertically grouped

Figure 94 Bedroom day view: ceiling light fixture and table stand

Figure 95 Bedroom night view: wall lighting fixture and table stand

6.3 Strength Enhancement: Surface

Inspired by the milk bottle, one of the goals of the project is to propose a design that utilizes thin material to provide strength for the designed functions. While the edges of the triangle are the major path of load delivery, the surfaces provide secondary support. However, the surfaces of the components seem flat, which does not give it the self-strength like the three-directionally curved forms that appear on milk bottles. With the low tensile strength of the material, the surface area of the triangle needs to be specially treated so that it can carry loads without severe deformation or breakage.

In the design, the triangle has 70 and 55-degree inner angles. The form is very similar to an equilateral triangle, which suggests that the three sides share similar stress when the load is applied uniformly or in the center. Therefore, under normal circumstances, the center of the triangle is as shown in the figure.

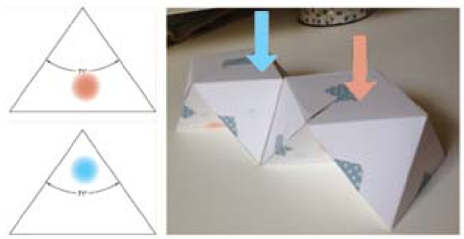


Figure 96 Load bearing point of flat surfaces

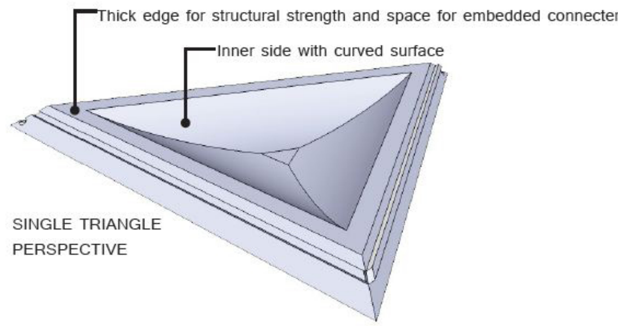


Figure 97 Embedded connecters and vault bottom

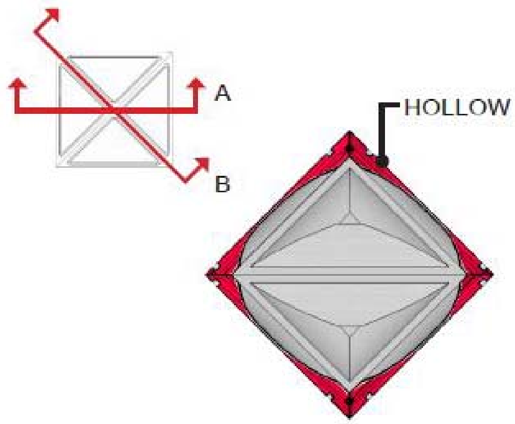


Figure 98 A: Cross section of diamond

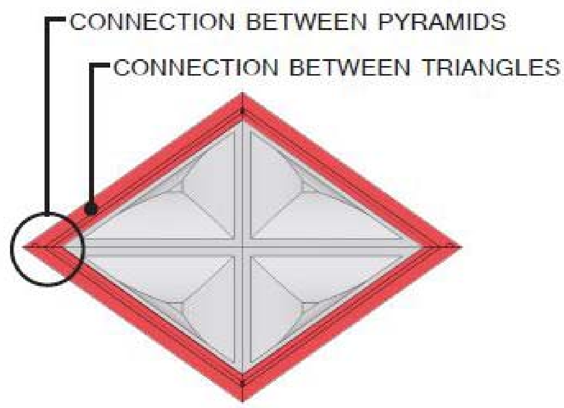


Figure 99 B: Diagonal section of diamond

However, due to the rotation of the diamond form and the shifted loading point, the three edges of the triangle may deliver different amounts of load to the edges below. Although the combination may remain stable because of the triangular framework embedded in the forms, the stress center of the triangle may differ under different circumstances.

For a single diamond, for example, when objects are placed in the middle of the triangle top, it is not as stable as putting the object closer to the tip of the diamond (See Fig. 93). Because of the triangular bottom of a diamond, it tends to tilt when the force is applied closer to the side of the bottom pyramid tip. The diamond is more stable when there are two or more of them assembled together. When this happens, the center of the load is closer to the edge of the pyramid.

Therefore, in most cases, the gravity point of the diamond is not in the center of the triangle. Instead, it is located closer to the angle of the side. In response to this characteristic as well as the principle of a bridge, the center of the triangle is thinner than the sides. This is an alternative to being three-directionally curved on the triangle surface in order to provide additional strength to the surfaces and form. The triangle piece is designed with a 360-degree vault on the inner side. Also, the edges of the triangle are thicker than the center, allowing space for the embedded connecters (See Fig. 94 & 95). The cross section shows that the inner space between the top and bottom of the triangle is hollow. The embedded connecters provide texture on the hollow surfaces to enhance strength.

6.4 Joineries

Inspired by the Miniwiz Pollybrick, an integrated joinery will be one of the important characteristics of the design. The flexible character of plastic allows a huge variety of joineries that can be easily connected and disconnected without additional tools or elements like nails and bolts. The linear tongue and groove is the main connecter considered in this design.

Because of the limited movement and tensile strength of HDPE, compared to steel, wood, and other conventional joinery materials, the design needs to consider distributing the tasks to different portions of the side. Based on the proposed function and assembly, the pyramid needs both inner and outer joints.

The joinery of the diamond is categorized into two types: inner and outer. The inner connecters are designed to assemble the unfolded piece into the pyramid and diamond forms. This connecter system allows the diamond to be installed easily. The outer connecters are used to assemble the diamonds into various forms for different functions. The two systems of connecters are both carefully integrated in the design to maintain the simplicity of the appearance.

6.4.1 Inner Joinery

The inner joineries of the planter have two important tasks: to connect the triangles into a pyramid and then a diamond and to provide water tightness between the edges. The connecters will be hidden under the pyramid for a clean surface on the outside. The tongue and groove joinery divides the product into two categories: groove edge and tong edge. The two categories of triangles are identical except for this aspect. The tongue and groove design avoids intersection in the middle of the edge, which may allow water leakage. Keeping the rest of the triangle, such as the connecters between each triangle and the outer joinery, consistent reduces confusion during installation.

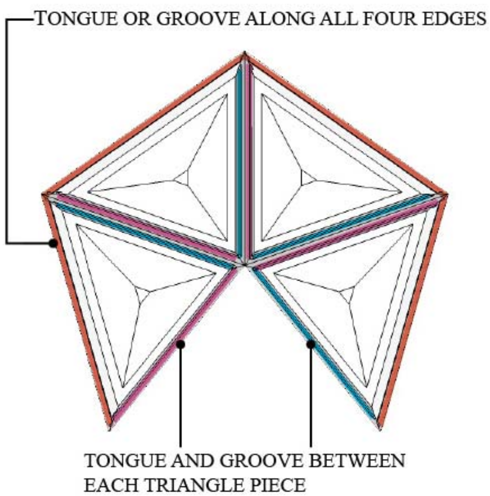


Figure 100 Inner joints on all edges: categorized into tongue or groove products (see red line)

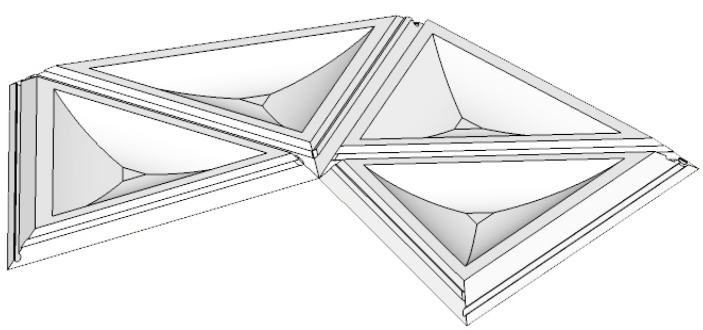


Figure 101 Inner connecter: groove along the four edges and joinery between each triangle

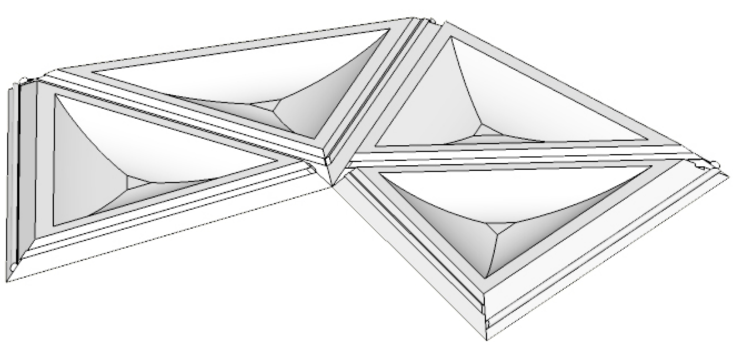


Figure 102 Inner connecter: tongue along the four edges and joinery between each triangle

6.4.2 Outer Joinery

The outer joineries are designed to assemble the diamonds together. The triangular surfaces of all the diamonds are the same, and with the variation between the 55 and 75-degree angles of the triangle, it is not difficult to orient the center point. The surfaces of the diamond have tongue and groove connecters that snap to each other when two diamonds are installed. Similar to the inner joinery, the outer joinery is also designed in a linear shape, which allows the groove to be embedded in the edges and for a simple appearance.

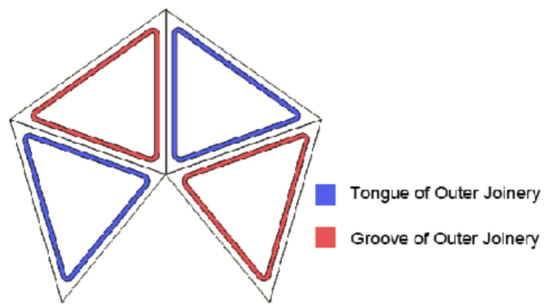


Figure 103 Outer joinery layout

The outer joints do not need to provide water tightness like the inner joineries, but they need to consider the convenience and flexibility of assembling the diamonds in different orientations. The tongue and groove of the pyramid alternates on the pyramid surfaces. This arrangement effectively reduces the confusion caused by misplacement of two halves of the connecter. By having the joints along the edges, the design also allows a usable area on the surface, which can be used to hold objects, such as mugs and notepads.

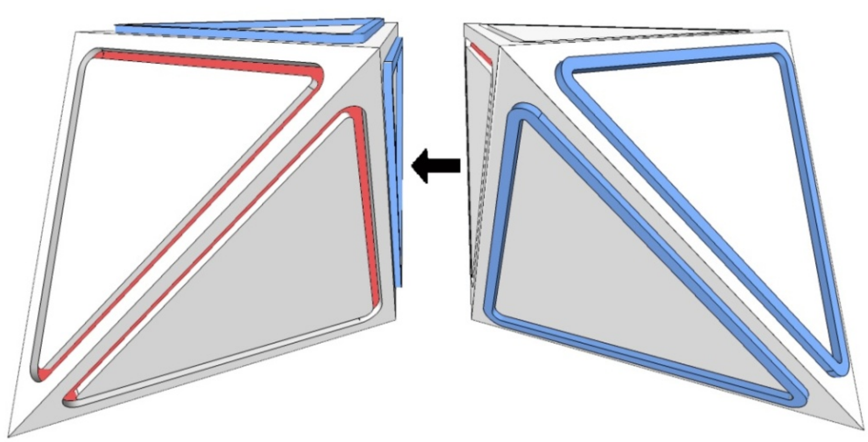


Figure 104 Assembly of two diamonds

6.4.3 Multiple Function Holes

When the diamond is used as a planter, the design needs to take drainage holes into consideration. The holes allow excessive water to flow to the planter on the bottom, thereby preventing the plants from flooding, conserving water, and preventing pollution of the indoor environment with excessive water. The holes are not in every corner of the planter, but rather, every other corner, so that users have an option of using or hiding the holes. Some planters do not need to drain water. For example, the bottom layer of the planters is used to hold the excess water and thus should not have holes.

The holes of the planter can also be used for cable connections when necessary. Unlike the initial design of planter pockets, the design of the HDPE diamond allows it to be free-standing and self-supporting. The cables are considered a secondary support when the installation involves anti-gravity setup, such as a ceiling panel. The cables allow the HDPE diamond panels to be hung on the ceiling, in order to create a different spatial experience for users. With a small stopper on the inner side of the diamond, the cable needs no additional bolts or clips to connect to the fixture, which allows it to be easily and completely removed, while maintaining the homogeneity of the product.

Figure 105 Proposed drainage hole

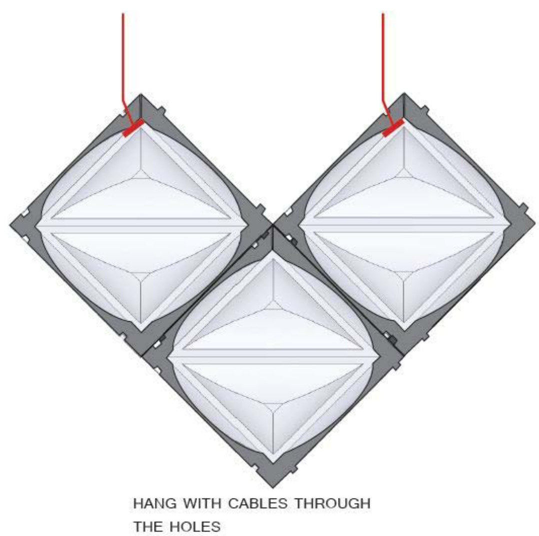


Figure 106 Proposed cable connecter for suspended ceiling

Conclusion

The design of the recycled HDPE diamond needs to reach a balance between functionality and aesthetics, as well as a balance between simplicity and comprehensiveness. By giving up the curvature, the diamond form provides a much higher functionality and workability than the initial design.

The design of the modular unit is not meant to be absolute, nor is the variety of assembly compositions. Instead, this design shows the potentials of a recycled product to embraces the lively sensation in an indoor environment, which shows the interaction between users and the product. This design encourages the idea of bringing products made of recycled material into people's everyday living, with the purpose of calling for an improved recycling rate in the future through the influence of accessible recycled products.

Chapter 7 Conclusion: an End is a Beginning

The design has proposed a solution to utilize the characters of recycled HDPE material to create a multifunctional product that can potentially increase the feasibility of recycling in the State of Hawai‘i . The design of the thesis does not represent the end of the study. Instead, it is the beginning of the conversation for other people who wants to carry it further in the future.

As a graduate student at the School of Architecture, the end of the thesis is also the beginning of my professional career.

The research and design of the recycled HDPE waste may not seem directly relevant to architecture. However, the two subjects share several similarities in the research, consideration, and design process. Not only does this study become a part of the fulfillment of my Doctorate of Architecture Degree, but it is also an abiding inspiration to my life.

7.1 Common Inspirations between the Thesis and Architecture

Architecture is a profession which turns the disadvantages of a site or building into an environment which presents an improved life style to the users. The thesis has also presented a new style of waste treatment which enhances the overall value of the recycled material.

Transform the Negatives into the Positives

In an architectural project, instead of blindly demolishing the entire building or site, the design ought to preserve the advantageous elements in the existing and revise the unwanted portions. Similarly, the elimination of plastic is not the best solution to the environmental issues. The pros and cons of the recycled waste can be enhanced or reduced through design.

To be fair to plastics, its existence shall not be a shame to the environment. Instead it is what human do with it that is the problem. Simply banning plastic will not fundamentally solve the problem because the environmental problem can be caused by a substitute of plastic. Instead of blaming the spread of polymer products, humans need to set up a convenient and systematic internal digestive system of plastic waste. Unlike the transfer of energy, plastics do not automatically transfer from on to another.

The main issue is the time it takes for plastic to degrade. It allows for the durability of the product. The characteristics of the plastic materials, such as HDPE and PET, can be much better presented in other applications than mere packaging. The design of the recycled plastic products can avoid undesirable properties in the material. Meanwhile, the design also enhances the advantages of the material through function, appearance, and application.

This thesis started with the idea of how to apply recycled plastic waste in building use, especially in construction. It has been proven that the material has a weaker strength than conventional building materials, and is not ideal for outdoor use due to the low UV-resistance. Although it is possible to enhance these characters by adding PC rebars and UV additives, it is more important to respect the existing properties of the material.

An architect makes design decisions based on the collective conditions in addition to the clients' opinions. The recycling of HDPE also ought to consider the realistic issues during the design process. Hence, the recycled HDPE material in the thesis is not emphasized at the building application, like it was originally planned for. The material is designed for interior settings, since this is more reasonable than forcing an outdoor application or structural element out of the material.

Repetitive Cycles between Issue Discovery and Improvement

An architectural design commonly goes through a series of discussions and alterations. When the current issues are solved, there are typically other aspects that need to be modified. This thesis has also encountered such a process. The flow chart shows the winding adventure to find a feasible solution to the environmental issues. It concludes that the main measure is the redesigning of the recycled HDPE product. Hence, the main goal of the design phase is to establish an example of the possible design.

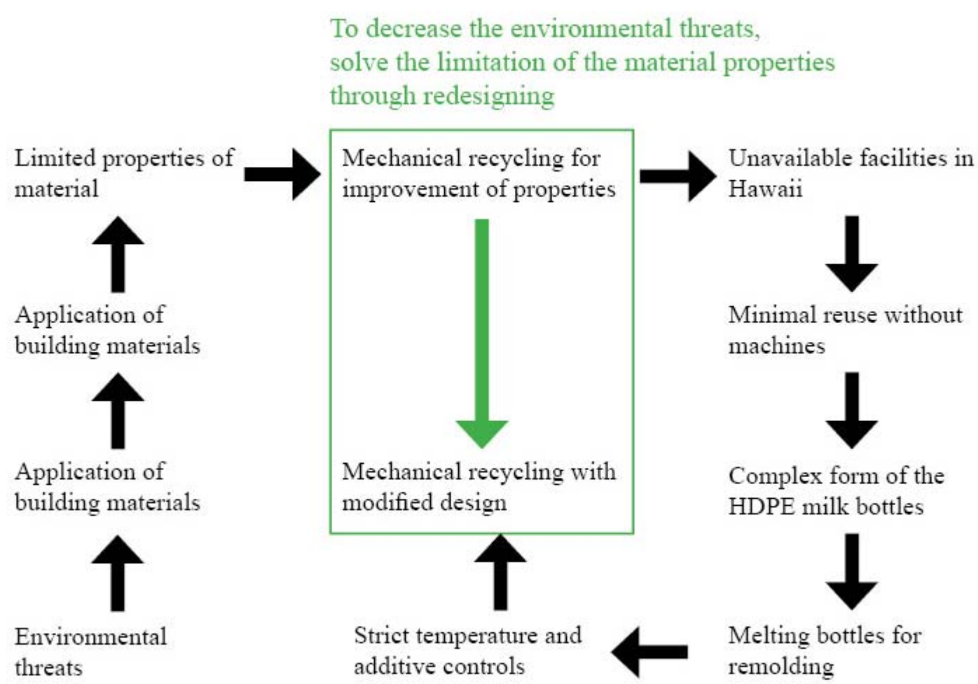


Figure 107 Research Flow Chart of the Thesis

The design in this thesis is not meant to be a fixed final design for the recycled HDPE materials; rather it aims to inspire the plastic recycling industry to a wide-spread introduction to the potential and new products. Therefore, the design phase is divided into two parts—the initial and proposed phase to show the intent of a constant revision of the product form, function, and application. In every revision, there will be new issues to be solved, and eventually the product will be highly feasible and adoptable.

7.2 Personal Growths

In the past 6 years of academic studies, we did not have to worry about local resources, available technology and equipments, and what a real client really likes. We designed based on our hypothesis and knowledge, while a lot of the time they may not be viable in reality.

From this project, I realize the importance of respecting the existing conditions and developing a design accordingly. The design project in this thesis is relatively realistic, since it depends on what is locally available, and what the future tendency will be. Although I have to go back and forth to work with this requirement, it makes the project much more rational and sensible. The end product results in the wide applicability and workability of the project and the start of making a difference.

The End Is Just a Beginning

As the author and student in the architectural program, this thesis is not to teach me what I researched for the topic. Instead, it is how to find the answer and how to make a decision. With the completion of this thesis, a brand new me with a new mind will begin.

❖ Be a Flexible Questioner

After this thesis, I have learned to not ask for the answer but the method. One could tell you an answer, but that does not represent our mind. Every time when I answer a question, it shall derive from a pile of data or facts as a foundation. Only when we obtain information from various perspectives we can decide what our answer is. During this process, it is necessary to be flexible about how to acquire the right information we need. The information is among us, some are mobile, and some are stable. The trick is how to find the stable info, and how to ask for the info. With the help of my committee, who has introduced me to a wide range of professionals, I was able to better understand what is going on, what the tendency is, and what the challenges are. These facts provide sufficient cause for me to continue the project.

During the research phase, I started from zero to a basic level of understanding of plastics. I also learn about the great recycling efforts that I have ignored for years. I looked into many of innovative projects that opened my eyes, giving me a new thought of what we as architects can do about the world. Through the research, I have convinced myself about the correct direction of my topic, which a lot of people don't want to get in the trouble with. I was once proud for challenging myself with a topic that I never know much of—materiality. This sense of success comes from being a questioner who is willing to step out of the specific profession.

❖ Be a Confident Decision Maker

First of all, no decision shall be made without being a questioner. There are many times when I make a hypothesis and jump into conclusion, but reality takes me in a different direction. Sometimes it is the lack of relevant knowledge that stops us from making a decision and sometimes, we just lack the exploratory spirit. Without these qualities, we are unable to build up our confidence in decision making, and I think has been my greatest challenge.

The design phase of this thesis has been the most difficult design challenge in all my years of academia. One of the biggest reasons is the inability to make a right decision. From the type of recycling method, design program, to design itself, I was not able to make the judgment call that worked the best with the project. In order to come out of the darkness, I need to reorganize my mind and find a better and stronger ground to support my decisions. It is very important to set one fundamental goal throughout the whole process, which shall be the basic evaluation of whether one step should be made, and whether it is reasonable to sacrifice one for another. For each decision made to approach the goal, it should not be easily altered by the new information. Instead, the decisions should try to accommodate the additional information in order to push forward the project.

The decision making process is not easy, but the hardest part is the uncertainty to the aspects that I do not clearly know about. Knowledge is the basics of every decision, and a wide range of interdisciplinary knowledge is the basics to a comprehensive judgment. I need to expand my knowledge base, open myself to different people with specific skills, and observe the world with mindful attention. Establishing the confidence and analytical skills will take time, but this is the only way to become a strong decision maker, who can be strong enough to carry out dreams.

Conclusion

In conclusion, the doctoral project means more than just a project to me. It is how I improve myself through facing the challenges that benefits me for the rest of my life. What bottle I use, and how I use the bottles is not the most critical part of this thesis. What matters the most is the attention we pay to the environmental issues and how we utilize our resources to resolve the problems.

Appendix A[127]

			Polyethylene							Clear Materials			
Property	**Units**	**PET-P**	**Nylon GSM**	**King Starboard Marine Grade**	**HDPE**	**UHMW**	**LDPE**	**PVC Type 1**	**Polypropylene**	**Properties for clear materials**	**Polycarbonate aka Lexan®, Hyzod®**	**Perspex**	**Acrylic**
Water Absorption (24 Hours)	%	0.7	1.2	-	0.03	0.01		0.1	0.008	Water Absorption (24 Hours)	0.02	0.03	0.03
Water Absorption (Saturation)	%	0.5	6.5	-		0.01		-	-	Water Absorption (Saturation)	-	-	-
Tensile Strength (73 °F)	PSI	12,400	12,500	3,800	4,600	4,750		7,000	4,800	Tensile Strength (73 °F)	10,500	10,000	10,000
Flexural Strength (73 °F)	PSI	-	16,400		1,400	3,500		12,500	7,000	Flexural Strength (73 °F)	12,000	17,000	17,000
Compressive Strength (10% Deflection)	PSI	15,000	10,000		4,570	-		10,830	6,720	Compressive Strength (10% Deflection)	11,000		
Shear Strength (73 °F)	PSI	8,000	11,000		3,380	-		9,240	5,710	Shear Strength (73 °F)	9,200		
Impact Strength, Notched Izod (73 °F)	Ft-Lbs/In.	0.6	.8 - 1.0		3	no break		1.3	1.9	Impact Strength, Notched Izod (73 °F)	13	0.9	0.9
Property	**Units**	**PET-P**	**Nylon GSM**	**King Starboard**	**HDPE**	**UHMW**		**PVC-1**	**Polypropylene**	**Properties for clear materials**	**Polycarbonate aka Lexan**	**Perspex**	**Acrylic**
Elongation at Break (73 °F)	%	20	50	>500	55	325		25	-	Elongation at Break (73 °F)	100	5	5
Tensile Modulus of Elasticity (73 °F)	PSI	423,000	400,000	120,000	170,000	90,000		410,000	190,000	Tensile Modulus of Elasticity (73 °F)	320,000	-	
Flexural Modulus of Elasticity (73 °F)	PSI	-	400,000	120,000	200,000	110,000		420,000	180,000	Flexural Modulus of Elasticity (73 °F)	375,000	400,000	400,000
Hardness - Rockwell & Burnell (73 °F)	Various Scales	M95	R120	68 Shore D	D69	R64		R112	R92	Hardness - Rockwell & Burnell (73 °F)	R118		M-93
Density	Lbs/cubic In	0.05	0.0418	0.0347	0.034	0.034		0.053	0.032	Density	0.043	0.044	0.044
Coefficient of Friction (Dynamic)	None	0.2	0.35			0.12		-	-	Coefficient of Friction (Dynamic)	-		
Wear Factor (K)	In-min/ Ft-Lbs-Hr	67	83			111		-	-	Wear Factor (K)	-	-	
Limiting PV	PSI/ FPM	3,000	3,000			2,000		-	-	Limiting PV	-	-	
Property	**Units**	**PET-P**	**Nylon GSM**	**King Starboard**	**HDPE**	**UHMW**		**PVC-1**	**Polypropylene**	**Properties for clear materials**	**Polycarbonate aka Lexan**	**Perspex**	**Acrylic**
Abrasion Resistance Index	None	-	-			10		-	-	Abrasion Resistance Index	-	-	-
Coefficient of Linear Thermal Expansion	In/In/F	-	5.0×10^5	1/32" / foot / 40 degrees F. or 6×10^5	1.25×10^4	7.2×10^5		7.3×10^5	1.20×10^4	Coefficient of Linear Thermal Expansion	3.9×10^5	1.3 x 10[illegible]	1.3 x 10[illegible]
Continuous Service Temperature - in Air (max.)	F	212	212	160	180	160		160	-	Continuous Service Temperature - in Air (max.)	475	180	180
Deflection Temperature (264 PSI)	F	215	200		151	116		154	-	Deflection Temperature (264 PSI)	539	-	-
Melting Point	F	491	430	250		-		360	-	Melting Point	-	-	-
Deformation Under Load (2000 PSI, 122 °F)	%	-	0.75			7		-	-	Deformation Under Load (2000 PSI, 122 °F)	-	-	-
Dielectric Strength	Volts/ Mil	385	550		500	-		552	-	Dielectric Strength	840		

[127] Machinist Materials, Inc., "Comparison Table for Plastics," Machinist Materials, http://www.machinist-materials.com/comparison_table_for_plastics.htm

Appendix B[128]

Data Table of Material Mechanical and Physical Properties

Mechanical Properties

www.matbase.com

Quantity	HDPE	PVC	PP	PC	Red Oak Wood Class IV (5-10 years)	Oregan Pine Wood Class III (10-15 years)	Purpleheart Wood Class II (15-25 years)	Indian Rosewood Wood Class I (>25 years)	Plain Concrete	Unit
Young's modulus	600 - 1400	2410 - 4140	1100 - 1550	2000 - 2400	12800 - 13000	11500 - 13500	1600 - 18000	0 - 12500	26000 - 26000	MPa
Shear modulus	700 - 800		300 - 500	700 - 700					2200 - 2200	MPa
Tensile strength	20 - 32	34.5 - 62	30 - 38	65 - 75	0 - 163	0 - 105	2.8 - 4.5	3.4 - 5.8	40892	MPa
Elongation	180 - 1000	14642	200 - 700	80 - 110					200 - 400	%
Compressive strength		55 - 90	38 - 55	86 - 86	47 - 61.2	43 - 52	72 - 85	56.5 - 65	40892	MPa
Fatigue	18 - 20	40732	24 - 24	39 - 39						MPa
Bending strength	20 - 45		32 - 50	90 - 90	100 - 130	68 - 82	135 - 163	0 - 119		MPa
Impact strength	0.27 - 10.9	0.22 - 1	0.27 - 1.1	6.5 - 9.5						J/cm
Yield strength				55 - 65						MPa

Physical Properties

Quantity	HDPE	PVC	PP	PC	Red Oak Wood Class IV (5-10 years)	Oregan Pine Wood Class III (10-15 years)	Purpleheart Wood Class II (15-25 years)	Indian Rosewood Wood Class I (>25 years)	Plain Concrete	Unit
Thermal expansion	110 - 130	50 - 80	58 - 150	66 - 66				36678	40828	e-6/K
Thermal conductivity	0.46 - 0.52	0.126 - 0.293	0.12 - 0.22	0.195 - 0.21		0.17 - 0.17		0.17 - 0.17	1.75 - 2.2	W/m.K
Specific heat	1800 - 2700	840 - 1170	1.927 - 2	1260 - 1500					840 - 840	J/kg.K
Melting temperature	108 - 134		165 - 165							°C
Glass temperature	0	80 - 90	0	150 - 150						°C
Service temperature	-115	-80	-115	-230						°C
Density	940 - 965	1350 - 1550	902 - 906	1200 - 1200	0 - 660	0 - 470	0 - 800	0 - 800		kg/m^3
Resistivity	5e+17 - 1e+21	1e+21 - 5e+23	1e+21 - 1e+21	2.1e+20 - 1e+21						$Ohm.mm^2/$
Breakdown potential	17.7 - 19.7	16.7 - 51.2	50 - 65	15 - 35						kV/mm
Dielectric loss factor	0.0005 - 0.0008	0.007 - 0.02	0.001 - 0.001	0.0006 - 0.0009						
Friction coefficient	0.25 - 0.3	0.45 - 0.55	0.3 - 0.5	0.52 - 0.58						
Refraction index	1.52 - 1.53	1.52 - 1.55	1.49 - 1.49	1.586 - 1.586						
Shrinkage	4-Feb	0.2 - 2.5	1 - 2.5	0.7 - 0.8		1.4 - 2.1		0.9 - 1.6		%
Water absorption	0.01 - 0.01	0.07 - 0.4	0.01 - 0.01	0.15 - 0.15					40739	%

Environmental Data

Quantity	HDPE	PVC	PP	PC	Red Oak Wood Class IV (5-10 years)	Oregan Pine Wood Class III (10-15 years)	Purpleheart Wood Class II (15-25 years)	Indian Rosewood Wood Class I (>25 years)	Plain Concrete	Unit
Eco indicator 95	2.782	2.95	2.82	4.364		1.79	1.38	1.43	0.672	mPt
EPS	768	550	846	1170		152	159	116	12.9	mELU
Ex (in) / Ex (out)	1.81387808	2.765104167	1.775212372	4.652836579	2.259365994	1.471226927	2.545549193	2.580144778	2.230919765	MJ/MJ
GER	75.74	54.94	82	105	35.8	38	38.7	39.2	0.831	MJ
Raw materials input	43.54607249	117.919479	4.7773	91.56949	2.763751002	2.13690751	2.762072807	2.644286776	3.120969787	kg
Solid	0.004010038	0.010791	0.03103	0.206973	0.100766303	0.101251638	0.101024149	0.101144553	0.00172695	kg
Eco indicator 99	0.339	0.219	0.38	0.434	0.64	0.388	7.5	9.48	0.0381	Pt

[128] "Data Table For Polymers: Commodity Polymers: HDPE," MATBASE, http://www.matbase.com/material/polymers/commodity/hdpe/properties (accessed August 25, 2011).

Appendix C[129]

Injection Mold Tooling Process Comparison

	Rapid Injection Molding	Low-Volume Injection Molding	Production Injection Molding
Part Size Limitation	20" x 20" x 3"	36" x 36" x 15"	36" x 36" x 15"
Part Geometry Limitation	No undercuts causing slide action in tooling; straight pull design	No geometry limits	No geometry limits
Part Material	Over 30 standard materials in stock including ABS, PC, PP, PE, Nylon 6/6, Acetal & Acrylic	Any commercially available material	Any commercially available material
Part Volume	36 in.^{3}	No volume limit	No volume limit
Parting Line Geometry	No limit	No limit	No limit
Draft	Draft required in CAD model	Draft required in CAD model	Draft required in CAD model
Tolerance Expectations	+/- 0.005", or per SPE standards for material	Tighter tolerances are possible	Tighter tolerances are possible
Surface Finish	Choose from 6 standard finishes	Any finish, including acid-etched finish	Any finish, including acid-etched finish
Customer Owns Tool?	No	Yes	Yes
Method of Tool Manufacture	CNC-only manufacturing, aluminum-only	No manufacturing limits, aluminum tooling	No manufacturing limits, tooling per customer specs
Lead Time	Standard: 10 Days for 10"x10"x3", 20 Days for 20"x20"x3" Expedited: 5 days, depending upon your geometry	Standard: 15-20 Days Expedited: 10 days, depending upon your geometry	Standard: 4-6 Weeks

[129] "QuickParts," Injection Molding Design Guide, www.quickparts.com/pdf/lvim/injection_molding_designguide.pdf (accessed October 10, 2011).

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